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GENERAL DYNAMICS
Convair Division

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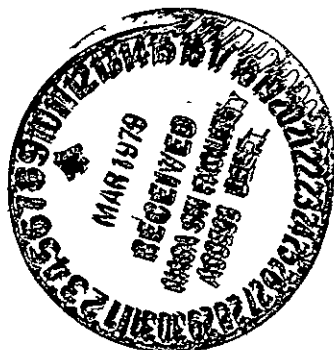
Three parallel truss structures, likely representing a large space structure component. Each truss is composed of a series of interconnected triangles, forming a long, narrow, and rigid framework. The structures are shown in perspective, receding into the distance.

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FOREWORD

This document is the Large Space Structures Fabrication Experiment Final Report. It is the final documentation of the work accomplished under NASA Contract NAS 8-32471.

The study was conducted from 14 February 1977 to 25 January 1978 by the Advanced Space Programs organization of Convair Division of General Dynamics. The study team operated under the technical direction of Hill M. Walker of the Process Engineering Division, Chemical and Non-Metals Processes Branch (EH 43) at Marshall Space Flight Center.

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A primary feature of graphite composite materials is their capability to be tailored to give near zero coefficient of thermal expansion in chosen directions of interest. This feature is embodied in the laminate selected for this study. The laminate has longitudinally unidirectional graphite fibers sandwiched between thin scrim glasscloth. In addition to modifying the laminate thermal expansion properties, the glasscloth serves the purpose of preventing fiber spreading of the graphite during the pressures of hot roll forming. In large scale production of material, modifications to laminate design to incorporate consolidation by weaving, both in the body and the selvage, can be effected to good advantage while retaining basic desirable properties. The laminate outer surface carries a thin thermoplastic film impregnated with titanium dioxide for thermal control.

Principal features of the beam fabrication machine shown in the accompanying illustration are as follows. Six reels of strip graphite/thermoplastic (GTP) material feed the forming units which produce three continuous cap section members and the beam cross-members. The cross-members are cut to length, positioned, and ultrasonically welded in place. Each bay of the beam is diagonally braced by crossing cords. These are dispensed and tensioned by an oscillating arm mechanism. The cords are fastened by welding them between the contact surfaces of cross members and caps. Differential cord tensioning is used to correct any inherent twist in the beam. Straightness within construction tolerances is achieved by synchronized cap extension.

The major study outputs are the conceptual design of a Shuttle flight experiment for on-orbit beam fabrication, and the preliminary design of a ground demonstration beam fabrication employing the rolltrusion process with GTP.

~~The study has shown the following:~~

1. The rolltrusion process is well adaptable to on-orbit operation.
2. Complexity of the proposed flight experiment is suitable to the proposed time frame - March 1982.
3. No high-risk development is foreseen.
4. The Large Space Structures Fabrication Experiment (LSSFE) makes an excellent, affordable, Shuttle experiment payload.

It is therefore recommended that NASA consider formalizing LSSFE as a Shuttle experiment payload for first flight in 1982.

SECTION I

INTRODUCTION

Preliminary space systems studies for the Space Shuttle era have focused attention on the need for deployment of very large space structures for a variety of potentially beneficial missions. Applications include communications, navigation, resources and environmental survey, area illumination at night, border and coastal water survey, and space platforms that provide common structural and operational support for various mission devices and facilities over long time periods. Of particular interest are envisioned satellite solar power stations that use inexhaustible solar energy flux to economically augment electrical energy supplies when terrestrial energy resources become inadequate or depleted.

A survey of preliminary structures arrangements for these systems and others reveals a substantial structural commonality. They are, with few exceptions, open truss and surface structures arrangements, (Figure 1-1). This fact simplifies the development of a universally applicable orbital fabrication technology. The development of such technology appears essential for economic systems viability in construction and in maintenance during the operational phases, which may stretch over decades.

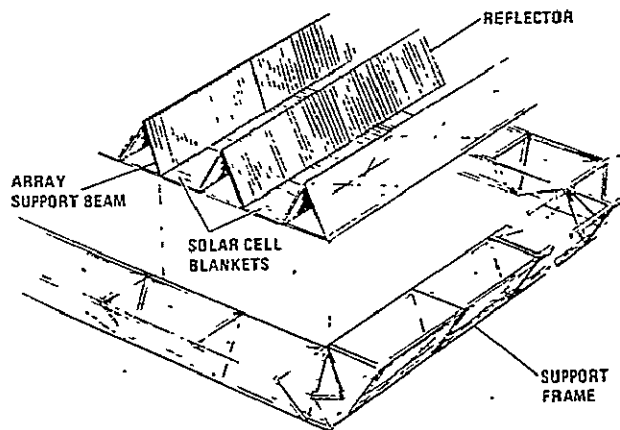


Figure 1-1. Solar Power Collector Construction Detail

Orbital fabrication technology should be, to the highest degree possible, generally applicable to all large space structure truss arrays. It should permit simple initial component deployment from the Space Shuttle payload bay or a free-flying fabrication pallet. Subsequent fabrication and assembly should use the initially erected structural elements as a reference for the assembly of subsequent elements and installation of other subsystems.

The most critical considerations for large orbital arrays, aside from those of high reliability and very long life, are dynamic and thermal response. Cumulative distortions due to thermal gradients in large arrays would cause major transient

geometric changes that impair performance of space systems to varying degrees. Large structure arrays of the type considered are inherently flexible and therefore exhibit long-period dynamic response to sharp temperature changes as they leave and enter the earth's shadow. The same pertains to excitation by docking forces, and thrust forces for orbital transfer and for control. This low dynamic natural frequency might have modes nearly resonant with pointing control frequencies. In combination this could lead to very complex and costly dynamic control systems.

Aside from the operational and dynamic control problems alluded to above, thermal expansion and contraction pose serious problems during construction in low earth orbit as the partially built arrays enter and leave the earth's shadow, particularly when docked supply vehicles and other masses such as manipulators are attached to the array. It would be difficult to quiet such arrays, and, with masses attached, serious strength problems could arise. It is therefore mandatory for the designer to select structure arrangements with the highest possible and practical stiffness, and materials with the lowest coefficient of thermal expansion combined with highest stiffness/density ratio. This requirement leads to the consideration of composite materials with graphite fiber reinforcement. Since the structural members must be shaped in space from basic material (strip) stock, graphite/thermoplastic, with its ready heat formability without loss of inherent stiffness/strength, is a natural choice.

Based on the above considerations and prior Convair experience in advanced composite material technology, particularly in graphite/thermoplastic hot forming development, this study was directed at conceptual solutions to the problems—associated with on-orbit fabrication of large space composite structures, their materials and processes.

STUDY OBJECTIVES

The primary objective of NASA's Space Structures Program is to acquire the necessary knowledge and techniques for on-orbit fabrication and assembly of large space structures. Specific supportive objectives of this study were:

1. Conceptual design of a large space structures flight experiment.
2. Preliminary design of a large space structures element fabrication machine for on-ground operation and proof of concept.

GROUNDRULES AND ASSUMPTIONS

The following groundrules and assumptions were made to scope the study tasks.

1. The dimensions of the experimental beam to be fabricated on orbit are assumed to be an equilateral cross-section one meter high and 100 meters long. See Figure 1-2 for typical details.

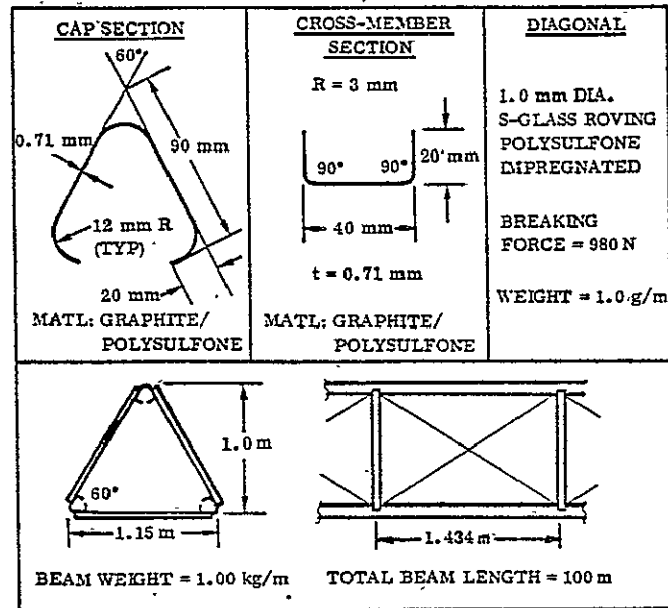


Figure 1-2. Beam Configuration Requirements Data

2. The beam members will be formed of graphite/thermoplastic material by means of the "rolltrusion" technique developed by General Dynamics.
3. Fabrication processes developed for beam members will be applicable to all future large space structures to the greatest extent possible.
4. The ground fabrication machine to be preliminarily designed will be functionally identical and physically similar to the machine concept developed for eventual flight experiment.
5. The on-orbit fabrication flight experiment will be assumed to be a payload on a Shuttle flight in March 1982. The mission will be accomplished in one shared flight.

6. The machine will be supported by the Spacelab pallet.
7. The experimentally fabricated beam will be sectioned and returned to earth for examination and testing as part of the flight experiment.
8. On-orbit dynamic and thermal response tests will be performed as part of the flight experiment.
9. Interfaces with the Shuttle will be governed by JSC 07700, Volume XIV.
10. The Spacelab design concept to be used is the European Space Agency (ESA) Spacelab baseline as defined in the Spacelab Payload Accommodation Handbook, Review Issue, PDR-B 1976, with subsequent updates.

STUDY FLOW PLAN

The study comprised three major tasks, namely:

- I. A materials and processes study for characterization of process variables and materials performance.
- III. A conceptual design for a Shuttle flight experiment and its associated requirements.
- V. The preliminary design of a beam fabricator incorporating rolltrusion shaping and joining devices for the purpose of ground demonstration.

Note that Tasks II, Beam Element Joining, and IV, Shuttle Interfaces, were deleted from the original study proposal owing to funding limitations. The task numbering system was retained for documentation consistency.

Figure 1-3 illustrates the basic elements of the study flow. The main line of progression is through Task III, wherein the eventual Shuttle flight experiment is conceptually designed, and through Task V, wherein the ground demonstration machine is pre-designed with relevance to the flight article, leading to the study output data.

Task I provided the selection of a graphite/thermoplastic laminate best suited to the space environment and the rolltrusion fabrication process. General Dynamics scheduled a substantial IRAD effort for 1977 in this area. Material tests relevant to this task were closely coordinated for maximum usefulness. Processing re-

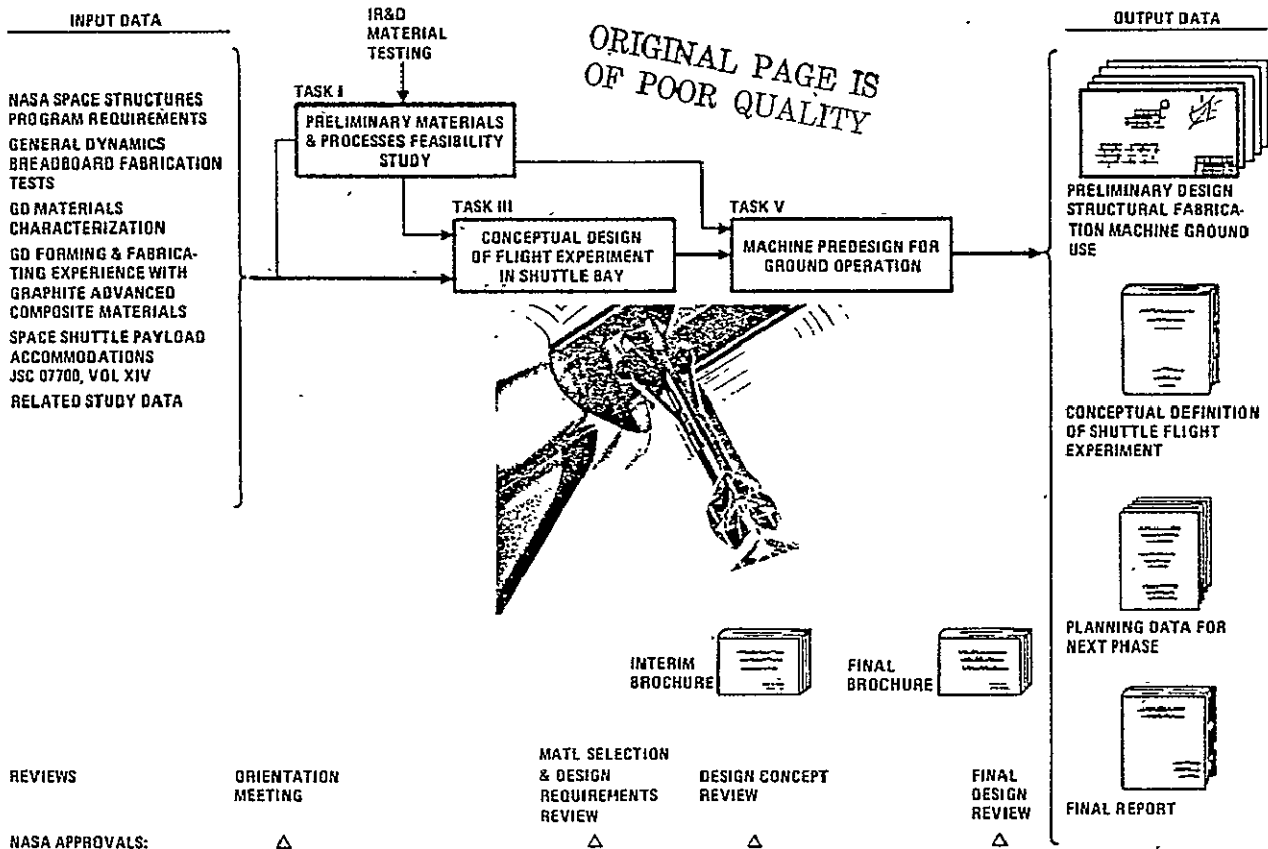


Figure 1-3. Study Flow Plan

requirements for forming and joining were evaluated to guide the design of the experimental space fabrication machine. Basic materials and processes to be input to Tasks III, and V were selected in conjunction with NASA by technical review.

The major task of conceptual design of the flight experiment was performed in Task III. Concepts for the total experiment system approach were evolved and compared. Related system factors of Shuttle environment, eventual operational usage and maximum usefulness of experiment results were considered. Operational procedures and requirements were examined and cost factors evaluated.

The outputs of all prior tasks were input to Task V for the preliminary design of a fabrication machine for ground operation.

Several reviews for NASA approval of study results are shown in Figure 1-3. An interim brochure and a final report have been prepared.

STUDY SCHEDULE

A top level study schedule is given in Figure 1-4. Duration of the three major tasks is shown, together with decision points for concepts development.

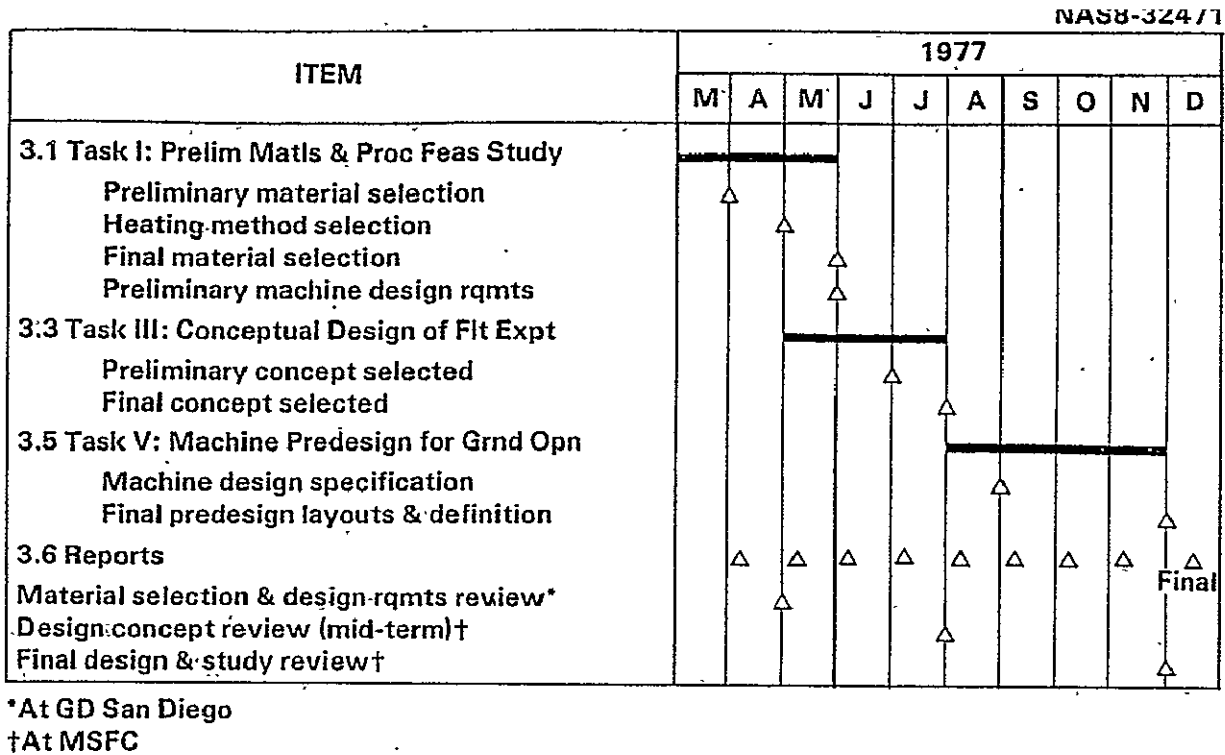


Figure 1-4. Overall Plan, Milestone, and Decision Schedule

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SECTION 2

MATERIALS AND PROCESSES

Objectives of the materials and processes study were to establish the materials requirements, characterize the selected material, study established manufacturing processes, and recommend the manufacturing methods to be used in a fabrication machine predesign for an on-orbit fabrication experiment in large space structures. The tasks were structured around advanced graphite fiber reinforced thermoplastic material and the unique rolltrusion concept for fabrication first demonstrated by General Dynamics in 1975 and currently the subject of a patent application.

2.1 MATERIALS

Composite materials, by their very nature, are capable of being tailored to specific property requirements. At this early stage of large space structures development a definitive set of structural requirements has yet to be set for a major application. However, there are certain generic characteristics that an appropriate composite material should possess, namely:

1. High specific stiffness (E/ρ) for structural efficiency.
2. Coefficient of thermal expansion close to zero.
3. Low cost for volume production.
4. Workability at any stage of fabrication.
5. Easy automated joining process
6. Low probability of interlaminar separation during forming.
7. Negligible outgassing

2.1.1 PHYSICAL PROPERTIES. A survey of the pertinent literature on graphite and Kevlar reinforced thermoplastics was conducted (References 1 to 11 in Table 2-1). Most of the work to date has been on A-S/P1700 graphite/polysulfone in the form of unidirectional tape. A very extensive design data program was run on this system by the University of Dayton Research Institute (Reference 1), and some property data is shown in Table 2-2. The Dayton study was conducted on prepreg provided by Hercules, A-S/3004, which is the Hercules designation for A-S/P1700. Extensive process optimization work has been conducted at Convair (Reference 5), and improvements should be readily obtainable with an optimized time-temperature-pressure cycle.

Samples of Type A-S/P1700 graphite/thermoplastic composite laminate submitted by Convair to NASA-MSFC in 1975 were tested to the requirements of the ATM Specification 50-MO-2442. The samples were heated to 100°C in a vacuum. No outgassing products were collected and this material is considered acceptable for space applications.

The literature contains little data on P1700 polysulfone reinforced with other graphite fibers. There is a large continuing effort being conducted by United Technologies (Reference 11) on HM-S/P1700. However, that effort is on filament wound material and is not directly applicable to this study. Included in Table 2-2 is some Boeing data (Reference 2) on P1700 reinforced with HM-S, T-300, Modmore I, and Modmore II. This is very preliminary data, and probably does not represent what would be obtainable after a concentrated effort. Of this data, the HM-S/P1700 is closest to what would be anticipated based on typical graphite/epoxy test results.

Table 2-1. Reference Literature

1. University of Dayton Research Institute, "Mechanical Property Data AS/3004 Graphite/Polysulfone Composite," Air Force Materials Laboratory, Contract F33615-75-C-5085, November 1976.
2. Hoggatt, J. T., "Study of Graphite Fiber Reinforced Thermoplastic Composites," Boeing Co. Report No. D180-18034-1, Naval Air Systems Command Contract No. N00019-73-C-0414, February 1974.
3. General Dynamics Convair Division, "Manufacturing Methods for Fabrication and Assembly of Advanced Composite Primary Structure," Air Force Materials Laboratory, Report No. AFML-TR-75-111, July 1975.
4. Voss, D. K., "Composite Fabrication with Graphite-Reinforced Polysulfone Prepreg Tape," Air Force Materials Laboratory, Report No. AFML-TR-74-217, November 1974.
5. Hertz, J., et. al., "High Temperature Graphite/Thermoplastic Composites," General Dynamics Convair Division, Report No. CASD-ERR-76-015, December 1976.
6. Hilzinger, J. E., et. al., "Advanced Composite Materials Evaluation," General Dynamics Convair Division, Report No. CASD-ERR-75-037, December 1975.
7. Merz, P. L., "Development of Graphite Reinforced Thermoplastic Technology," General Dynamics Convair Division, Report No. CASD-ERR-74-043, December 1974.
8. Bauer, J. L., et. al., "Advanced Composites Materials Technology," General Dynamics Convair Division, Report No. CASD-ERR-74-058, December 1974.
9. Maximovitch, M. G., "Thermoplastic Composite Development," General Dynamics Convair Division, Report No. CASD-ERR-73-032, December 1973.
10. Hoggatt, J. T. and Von Volkil, A. D., "Evaluation of Reinforced Thermoplastic Composites and Adhesives," Boeing Co. Report No. D180-17503-3, Contract N00019-74-C-0228, March 1975.
11. Novak, R. C., "Graphite Reinforced Thermoplastic Resins," United Technologies Research Center, NASA Contract NAS3-17833, Report No. NASA CR-134881, July 1975.

Some testing has been conducted at Convair (Reference 7) on graphite fabric (Style W-133) reinforced P1700. That data in addition to data on the same graphite fabric with epoxy resin is shown in Table 2-3. Graphite/epoxy data on other styles of graphite fabric are also presented in Table 2-3. The testing of graphite fabric reinforced polysulfone compares favorably with that of graphite fabric reinforced epoxy.

Ideally, a single ply, full-thickness fabric would be desirable for in-space processing. This would eliminate the ground compaction step necessary with unidirectional tape layups and would eliminate potential local ply separation during in-space forming. The graphite fiber should ideally be a high modulus fiber which is inexpensive. At this time, Convair is considering HM-S fiber as the baseline for woven fabric because of its high modulus, past history, and availability. Other fibers being

considered are Modmore I, Fortafil 5, and Thornel Type P. The latter is Union Carbide's pitch base fiber. At present, this fiber has the proper modulus, but rather low strength. Testing at Convair on Thornel P/934 graphite/epoxy has demonstrated the ability to translate the fiber modulus into composite modulus. With the low cost projections for pitch fiber, however, it becomes a leading candidate for in-space processing.

Table 2-2. Test Results on Unidirectional Graphite Reinforced P-1700 Polysulfone

Composite Properties	Fiber Type				
	A-S *	HM-S	T-300	Mod. I	Mod. II
Longitudinal Tensile Strength, ksi	188	175	155	90	100
Longitudinal Tensile Modulus, msi	16.3	31.5	20.0	29	21
Longitudinal Poissons Ratio	0.34				
Transverse Tensile Strength, ksi	5.0				
Transverse Tensile Modulus, msi	1.15				
Transverse Poissons Ratio	0.024				
Longitudinal Compression Strength, ksi	102				
Longitudinal Compression Modulus, msi	17.3				
Transverse Compression Strength, ksi	18.9				
Transverse Compression Modulus, msi	1.60				
In-plane Shear Strength, ksi	16.0	9.3	11.6	8.9	10.6
In-plane Shear Modulus, msi	0.56				

* Data from F33615-75-C-5085 (Reference 1) and based on panels having fiber volume of 57 to 58 percent. All other data from N00019-73-C-0414 (Reference 2) and is normalized to 60 percent fiber volume.

2.1.2 LAMINATE DESIGN. Three forms of laminate design have been considered for large space structures use:

1. Hybrid of 0° graphite tape sandwiched between thin layer of glass or Kevlar fabric.
2. Single ply of specially woven fabric.
3. Multiple laminate

All three forms have the promise of doing the job efficiently. Each has pro's and con's as follows:

1. Sandwiched 0° Tape

This concept uses several plies 0° pitch graphite sandwiched between single plies of 104 or 120 glass cloth. The number of 0° plies and the thickness of cloth are determined by structural requirements (loads and stiffness).

Table 2-3. Typical Properties of Graphite Fabric Reinforced Composites

Laminate Composition and Properties *	Fabric Style				
	Fiberite W-133	Fiberite W-133	Fiberite W-134	Fiberite W-176	Fiberite W-185
Type of graphite	T-300	T-300	T-300	T-300	Modmor III
Filaments per yarn	3,000	3,000	3,000	1,000	20,000
Weave	8H Satin	8H Satin	Plain	5H Satin	Plain
Thread Count (Warp x Fill)	24 x 23	24 x 23	12 x 12	24 x 24	4 x 6
Resin	934 Epoxy	P-1700 Polysulfone	934 Epoxy	934 Epoxy	934 Epoxy
Ult. Tensile Strength (warp), ksi	90	88	80	90	42
Ult. Tensile Strength (fill), ksi	90		80	90	60
Tensile Modulus (warp), msi	10		9.5	10	5.6
Tensile Modulus (fill), msi	10		9.5	10	8.6
Flexural Strength (warp), ksi	120	118	110	125	67
Flexural Strength (fill), ksi	120	123	110	125	74
Short Beam Shear Strength (warp), ksi	9.0	8.5	8.5	8.5	5.7
Short Beam Shear Strength (fill), ksi	9.0		8.5	8.5	5.0
Fiber Volume, %	65	60.1	65	65	65
Cured Ply Thickness, in.	.013	.0145	.007	.0045	.025

*All graphite/epoxy data reported was measured by Fiberite.

Pro's

- Allows superior fiber translation of properties in graphite.
- Flexible Concept - gages can be changed easily with given constituent materials.
- Low cost in both R&D phases (now) and in production phases (later).
- Lends itself to continuous processing at the fiber prepregers facility.
- Requires low forming energy in space (See Figure 2-1).
- Inhibits transverse heat flow.

Con's

- Low stiffness of glass dilutes stiffness-to-weight ratio by a small percent.
- Lower conductivity of thin glass may slow laminate heatup rates.

2. Woven Fabric

This concept uses a single ply of a fabric woven such that 0, 90, and ± 45 degree fibers are present; the amounts of each being dependent on the

structural requirements. The fabric would be required to be thicker than that presently used in aerospace applications and would have to be specifically designed to meet space platform or other specific load requirements. Present graphite fabric weavers are in production on $0^\circ/90^\circ$ fabrics and there is a near term possibility for a $0^\circ/45^\circ$ fabric. However, there is little nearterm hope of weaving $0^\circ/\pm 45^\circ$ fabrics. The latter can be obtained by braiding, but results in a starting material that is non-uniform in thickness.

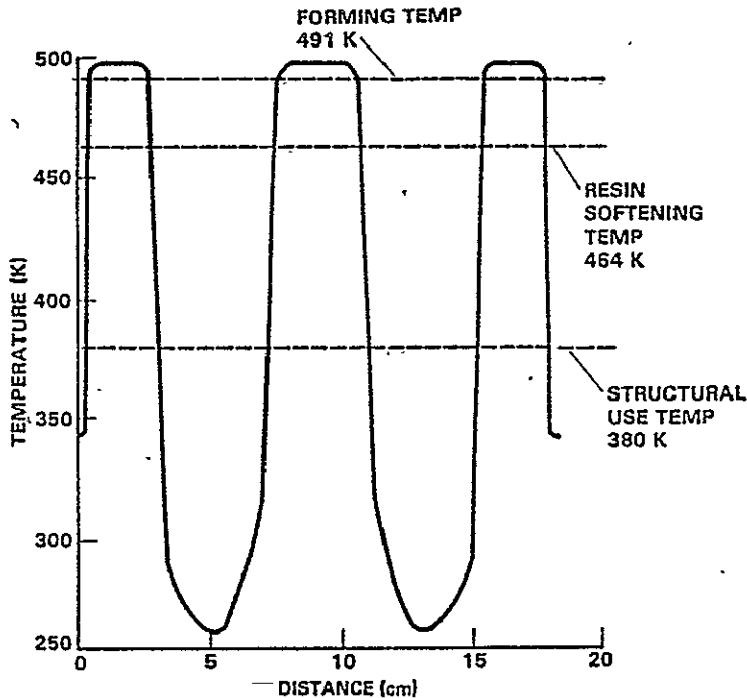


Figure 2-1. Temperature Profile Across Cap Section Strip at Heating Section Exit

In order to investigate the one-ply woven concept under parallel IR&D work, five pounds of W-185/60 prepreg was purchased from Fiberite. The W-185 fabric was chosen because it was thick and was readily available. The prepreg obtained by Convair contained the Union Carbide P-1700 polysulfone as the matrix. Flexure and tensile testing were conducted on specimens cut in both fill and warp directions from the 4-ply laminate. The test results are given in Table 2-4.

The data generated shows good translation of modulus and reduced strength resulting from the thicker fabric. For most

in-space fabrication of composite hardware, the strength and modulus values obtained would be adequate. In addition, the fabric must be designed for the specific application. Hybrids can be woven so that there are one or more fibers in both warp and fill directions and in varying concentrations. Less expensive fibers such as Union Carbide's pitch base graphite (Type P), Kevlar-49, fiberglass, etc., can all be incorporated into a finalized fabric design.

Pro's

- a) Prevents delamination in forming process.
- b) Single ply has excellent interlaminar properties.
- c) Woven material may form more easily in the Rolltrusion machine.
- d) With glass or Kevlar fill fibers will require low forming energy consumption in space.

Table 2-4. Test Results on W-185/60 Specimens

Test Direction	Tensile Strength ksi	Tensile Modulus ksi	Flexure Strength ksi
Fill	58.1	6.6 to 9.1	78.1
	66.4	9.2	77.4
	<u>49.4</u>	<u>6.1 to 8.4</u>	<u>81.0</u>
AV.	58.0	8.1	75.5

- e) Lends itself to continuous processing in production.
- f) Good through-the-thickness conductivity for heat-up/cool-down.

Con's

- a) Special fabrics needed for each application.

- b) Higher costs for small quantities.
- c) Crippling strength likely to be lower.
- d) Type P graphite is expensive to weave.
- e) Accentuates transverse heat flow.

3. Multi-ply Laminates

Multi-ply laminates are the traditional form of laminate used in composite structures. They consist of several layers of 0° graphite plies oriented in the directions best suited to meet the requirements of a particular structural element. As such, they can be optimized for each application. The process of laying up multi-ply laminates is currently best suited, however, to wide sheets of finite length material. Air Force funded research by Hercules Inc., on automated multi-ply laminate (broadgoods) layup can reduce the high cost of multi-ply laminates in the future resulting in a material which can be slit to the width needed for LSS application.

Pro's

- a) Allows superior fiber translation of properties in graphite.
- b) Flexible concept.
- c) Laminate can be optimized for each application.

Con's

- a) In an early state of development.
- b) Will require a large investment in facilities at the material supplier end for thermoplastic matrix materials.
- c) Inherently higher cost starting material (more production steps).

Recommendations

For near term development the most flexible, least cost, and least risk approach appears to be the sandwiched 0° tape. A typical generic laminate which is weight effective is $[120/0_2/120]_T$ glass/VSB-32T graphite/glass in a polysulfone matrix

($t = 0.71$ mm). This system was set up as the baseline material for the program. HMS fiber could be considered if VSB-32T pitch fiber in polysulfone is not available for early development. Figure 2-2 illustrates the laminate construction. For longer term development more investigation of a tailored, single ply fabric should be conducted. Properties of the selected baseline are given in Table 2-5. A preliminary worst case analysis for beam fabrication while attached to the Orbiter, vernier RCS firing, indicated a conservative minimum required value for cap section stability of 20.7 MN/in^2 (3000 psi). Pending test results, the shear capability provided by glasscloth of at least 0.1 mm (.004 in) thickness on each side is considered reasonable.

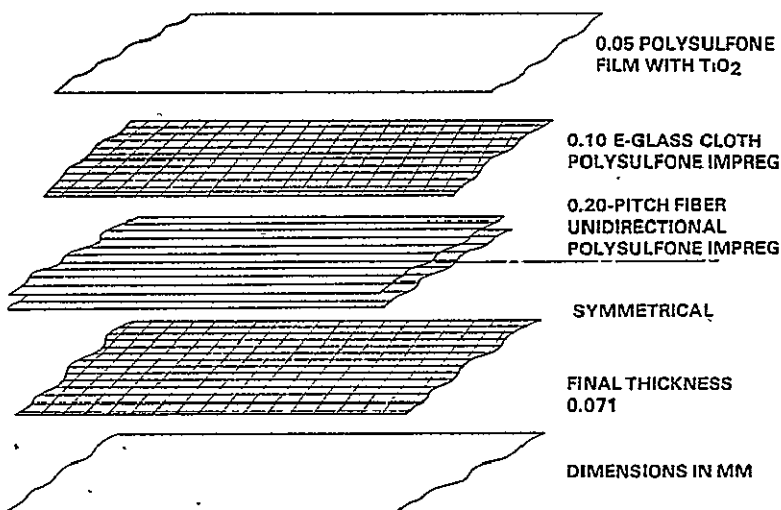


Figure 2-2. Baseline Laminate Construction

2.2 PROCESSES

The fundamental rolltrusion process feeds strip-form graphite thermoplastic material from a reel through a heating section, a roll-forming section, and a cooling section. In a beam-builder machine multiple heads provide formed material in a continuous process. This material is joined and cut as required for the beam/truss assembly operations.

This study was performed to evaluate processing methods and requirements for energy-

efficient forming and joining of graphite/thermoplastic (GTP) materials. The prime effort was devoted to heating methods for bringing the GTP up to forming temperature and forming methods for preparing the required cross-section.

Groundrules and Assumptions

1. The maximum processing power available from Shuttle Orbiter is 7 KW average, 12 KW peak for not more than 15 minutes in any three-hour period at 27 Vdc min. (ref. JSC 07700 Vol. XIV).
2. Nominal truss forming speed is 18.3 mm/sec (3.61 ft/min) average.
3. Initial material temperature is 255K (0F).
4. Material temperature in forming zones must reach or exceed $490 \pm 15\text{K}$ ($425 \pm 25\text{F}$).
5. No free debris must be released by any process.

Table 2-5. Comparative Laminate Data

PROPERTY	UNITS	ALTERNATIVE LAMINATES					
		1		2		3	
Layup (See notes)		(104/O ₂ /104)		(120/O ₂ /120)		(120/O ₃ /120)	
t	mm (In)	0.46	(.018)	0.61	(.024)	0.81	(.032)
E _x	GN/m ² (MSI)	178	(25.83)	138	(20.01)	153	(22.18)
E _y	GN/m ² (MSI)	6.33	(0.92)	9.84	(1.43)	8.81	(1.28)
μ	-	0.19		0.17		0.17	
G	GN/m ² (MSI)	5.92	(0.86)	5.23	(0.76)	5.37	(0.78)
α _x	μm/m/°K (μin/in/°F)	-0.623	(-0.348)	-0.292	(-0.162)	-0.445	(-0.247)
α _y	μm/m/°K (μin/in/°F)	26.9	(14.92)	19.4	(10.78)	20.9	(11.64)
F _{Tx}	MN/m ² (KSI)	402	(58.5)	312	(45.3)	346	(50.3)
F _{Cx}	MN/m ² (KSI)	402	(58.5)	312	(45.3)	346	(50.3)
F _S	MN/m ² (KSI)	69.5	(10.1)	60.5	(8.8)	63.3	(9.2)
F _{Ty}	MN/m ² (KSI)	33.0	(4.8)	52.3	(7.6)	46.8	(6.8)
F _{Cy}	MN/m ² (KSI)	53.7	(7.8)	121	(17.6)	109	(15.8)
ρ	kg/m ³ (Lb/In ³)	1774	(.0641)	1835	(.0663)	1813	(.0655)

- Note: 1) Graphite laminate thickness = 0.20 (.008")
104 glass thickness = 0.025 (.001")
120 glass thickness = 0.10 (.004")
- 2) Laminate data was based on minimal test data and required use of "similar" material systems data for several parameters including CTE.

Requirements

The heating task is to bring a flat strip of the composite material to a temperature in localized bend areas that will allow it to be formed into the proper shape. For the cap section the material to be formed is 18 cm. (7.1") wide by 0.71 mm (.028") thick and up to 100 meters (328 ft) long. The composite strip will be traveling at a rate of 2.2 meters per minute for 40 seconds and then will pause for 40 seconds while cross members are attached to the newly formed cap sections. One half of the required heat energy input will be supplied during each 40 second interval. Since the strip has to be maintained at the forming temperature during passage through the forming section some make-up heating will be required.

The initial heating must take place at the 18.3 mm/sec average forming rate. The heating rate for one cap will be:

$$\begin{aligned} \text{Heat Rate} &= \text{volume rate} \times \text{density} \\ &\quad \times \text{specific heat} \\ &\quad \times \text{temperature rise} \end{aligned}$$

For the postulated conditions net required energy input to the material is 464 watts, comprising 190 watts to the center strip and 137 watts to each edge strip.

The specimen material consisted of a 0.40 mm thick layup of graphite filaments, unidirectional (longitudinal) impregnated with polysulfone, a 0.10 mm polysulfone impregnated glass cloth layer on both sides and a 0.05 mm thermal protection layer of polysulfone containing titanium dioxide on both sides. See Figure 2-3.

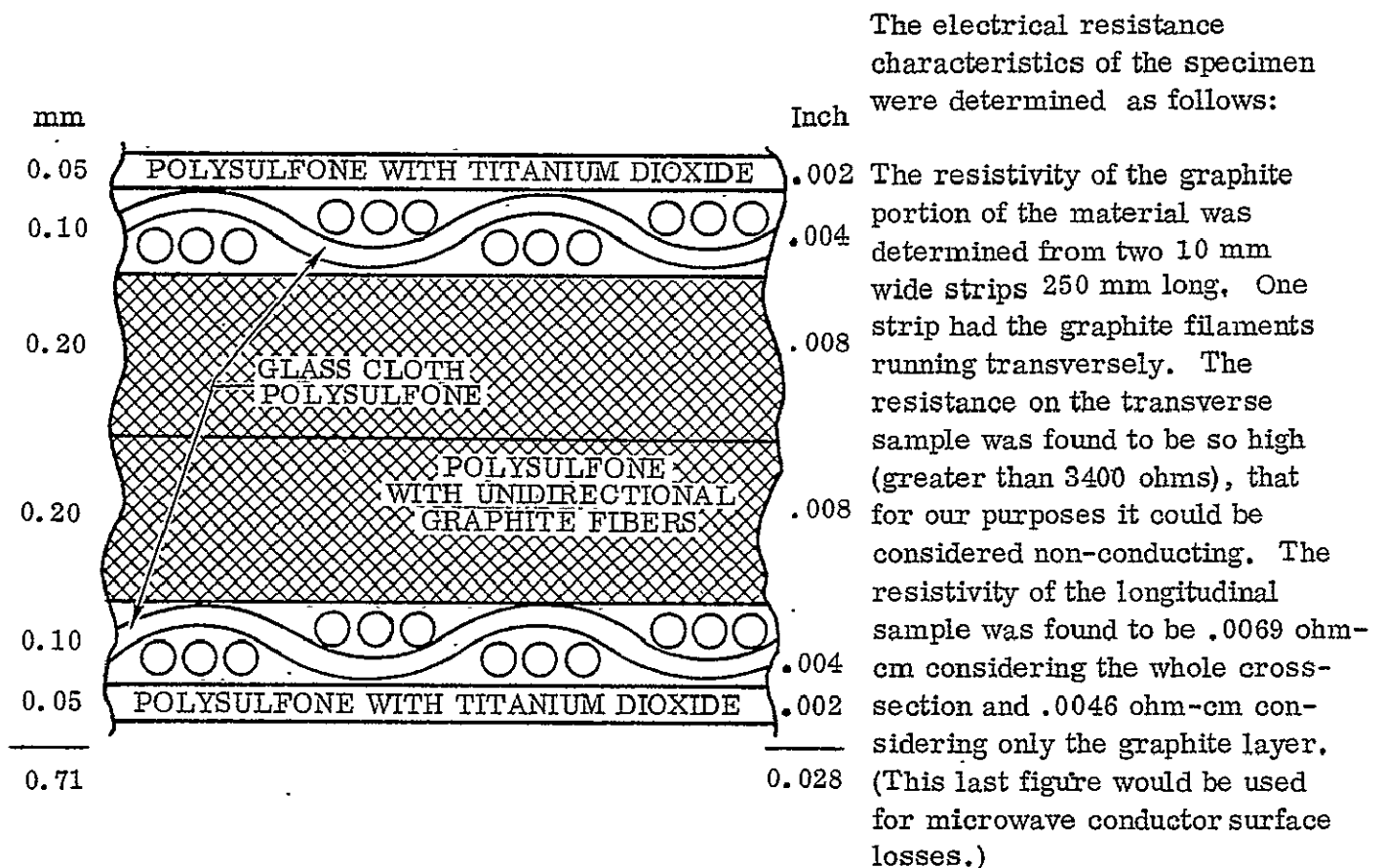


Figure 2-3. Specimen Cross Section

Since the graphite is a conductor and the glass and polysulfone are not, dielectric losses stop at the surface of the graphite and the graphite must be considered a capacitor plate. Since dielectric exists on both sides of the graphite, it assumes a neutral role and should be effectively grounded.

In addition to radiative heating from a resistance element three types of high frequency heating were considered.

1. Radio frequency treating
2. Microwave heating
3. Induction heating

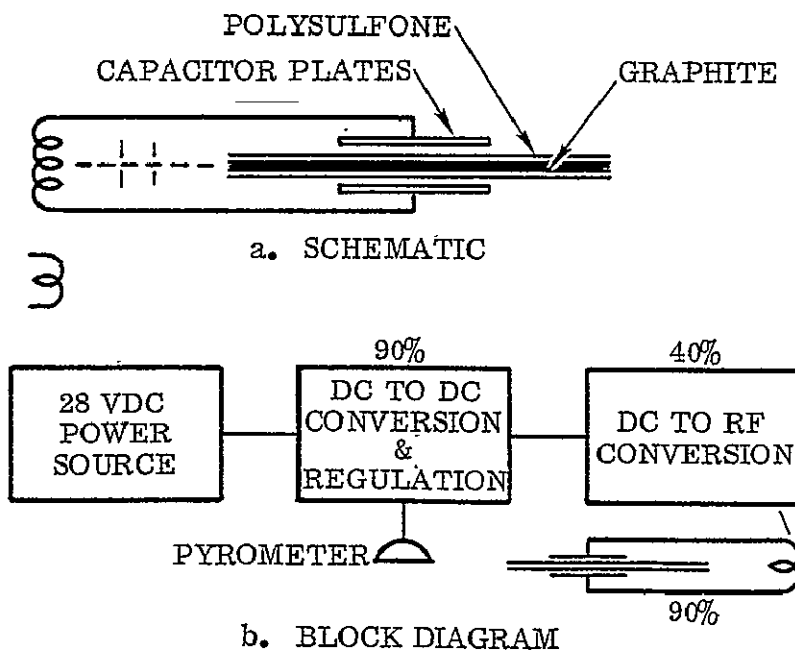
The key factor in comparative evaluation of heating methods is energy efficiency as follows:

$$\text{Percent energy efficiency} = \frac{\text{Energy Out}}{\text{Energy In}}$$

Energy Out = thermal energy received by the work piece

Energy In = electrical energy supplied to all necessary equipment

2.2.1 RADIO FREQUENCY HEATING. For this application, the tooling constitutes capacitor plates as does the graphite layer in the center of the specimen. Since the graphite is moving and can have no direct electrical contract, it is carried as a neutral in a balanced tank circuit. See Figure 2-4a for schematic. The RF energy stored in the capacitor is dissipated directly in the polysulfone (dielectric). If this heating takes place at a very rapid rate, the energy conducted to the tooling is mini-



mized, yielding a highly efficient process. The tooling requirements would appear to be less severe than those for microwave heating since, by proper tool and electrode design, the RF fields within the tool can be reduced to near zero. The technique has been successfully used in curing graphite/epoxy laminates. The dielectric properties of the polysulfone determine the heating rates that can be achieved. These in turn will influence the effectiveness of the method and tool requirements.

The RF heating phenomenon is based upon the dissipation of energy in a dielectric medium

Figure 2-4. Dielectric Heating

in an electromagnetic field. The power dissipated is given by $P = \omega \epsilon \tan \delta (E_0^2 / 2)$, where ω is the angular frequency of field, ϵ and $\tan \delta$ are the dielectric constant and loss tangent of the (thermoplastic) medium, and E_0 is the amplitude of the electric field. A high-loss material (that is, a material with a high loss tangent and dielectric constant) can be heated directly by this technique and is desirable. Low-loss materials require a high-loss secondary medium to act as a heating element to indirectly heat the low-loss material.

The frequency of the rf energy is inversely proportional to both the loss factor of the polysulfone matrix and the square of the electrode voltage. Since the loss factor is low and tends to further decrease with increasing frequency and the electrode voltage must be maintained at low levels to avoid arcing due to outgassing and low ambient pressure, the frequency for dielectric heating will tend to be in the microwave range where rf conversion efficiencies are relatively low, about 40%.

Figure 2-4b is a block diagram of part of a system showing the power source and conversion and indicating a servo-control from a pyrometer which will vary the power as needed to maintain the temperature. Typical stage efficiencies are shown which will total a fairly low efficiency overall (32.4%).

2.2.2 MICROWAVE HEATING. For this case, resonant cavities would be used for power transducers. Losses in the specimen would be both dielectric and conductive. There would also be losses in the other walls of the chamber. This would tend to lower the efficiency of the transfer. There would be chambers above and below the specimen that would be independent. Polarization would have to line up with the graphite to produce consistent results.

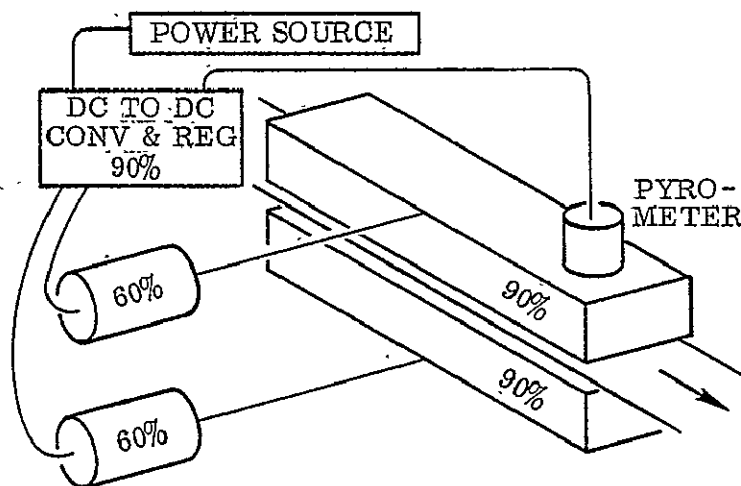


Figure 2-5. Microwave Heating

Although this method is practical for flat areas of the specimen, it would become increasingly more difficult in the formed areas of the specimen.

Figure 2-5 shows a semi-pictorial block diagram of a dual system. Magnetrons in the high frequency range would be the most efficient for this application. Stage efficiency for the highest power application are shown. Lower power levels used for holding temperatures would be less efficient in the same system. The overall

efficiency would be about 48%.

2.2.3 INDUCTION HEATING. Figure 2-6 shows methods of using inductive heating to heat specimen plates and tooling parts from which heat could be transferred to the laminate. The composite itself cannot be heated directly since the unidirectional graphite fiber conductivity does not provide for a loop path for the current.

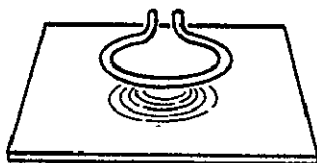
Some of the tooling could be heated this way due to the geometry of the parts. There is little reason, however, since plates and wheels can be heated directly more efficiently.

Inductive heating requires DC to DC conversion, DC to high frequency conversion and transmission and stray field and copper losses. Forty percent efficiency would be optimistic.

2.2.4 RESISTANCE HEATING. The objective of this study was to determine the most efficient and reliable means of heating graphite/polysulfone strip material to its required forming temperature using electrical resistance heating.

The following groundrules and assumptions were made:

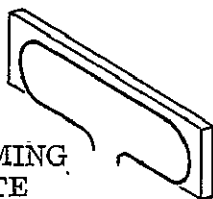
1. Heat will be applied only in those areas where forming is required to maximize thermal efficiency and to aid the forming or shaping process.
2. A restart capability is required following an interruption where partially formed materials may have cooled between forming roller stations.
3. The material is that described in Figure 2-3 with the following additional assumed properties:



a. INDUCTION IN A FLAT SPECIMEN



b. FORMING ROLLER



c. FORMING PLATE

- a) Its forming temperature is $490 \pm 15\text{K}$ ($425 \pm 25\text{F}$).
- b) Its mean specific heat from 255K (0F) to 490K (425F) is $0.25 \text{ cal-g}^{-1}\text{K}^{-1}$ ($0.25 \text{ BTU-lb}^{-1}\text{F}^{-1}$).
- c) Its mean density is 1794 Kg-m^{-3} (112 lb-ft^{-3}).
- d) Its thermal conductivity is a constant value of $0.72 \text{ Wm}^{-1}\text{K}^{-1}$ ($5 \text{ BTU-in-hr}^{-1} \text{ ft}^{-2} \text{ F}^{-1}$) in the directions perpendicular to the fibers, and $3.6 \text{ Wm}^{-1} \text{ K}^{-1}$ ($25 \text{ BTU-in-hr}^{-1} \text{ ft}^{-2} \text{ F}^{-1}$) in the directions parallel to the fibers.

Figure 2-6. Induction Heating

4. The material will be 0.71 mm (0.028 in.) thick, 18 cm (7.1 in.) wide, and will be processed at an average rate of $1.1 \text{ m} \cdot \text{min}^{-1}$ ($3.6 \text{ ft} \cdot \text{min}^{-1}$) for a total length of 100 m (328 ft).
5. The ambient temperature of the material immediately prior to heating is 255K (0F).
6. Where contact occurs, perfect thermal transfer is assumed.
7. The power source for the heating of the material will be a 28 volt D.C. Shuttle fuel cell, with a 7 Kw average, rated capacity, located on the space shuttle within 6.1 m (20 ft) of the working area.
8. The space environment results in no measurable external convective or conductive gas heat transfer, and no radiation energy input except as designed.

Since the source of energy has been assumed to be the 28 volt D.C. Shuttle fuel cell, a direct resistive heating process can use this energy source directly with no intermediate energy conversions required. This immediately puts this choice ahead of all other choices, since most energy conversions are fairly inefficient. Even a simple D.C. to A.C. conversion, which is only the first step required for eddy current or induction heating, etc., is at best only 90% efficient.

To design a resistance heating system, there are several factors that must be considered. Basically, we must consider the transfer of electrical power from the fuel cell source to the working area (an assumed distance of 6.1 meters); the change of electrical energy to heat energy; the transfer, if necessary, of that heat energy by conduction or radiation into the specimen; and the losses that may exist at or in each of these areas. Some of these factors are interdependent. Therefore, an iteration process is required to compute the final results.

To evaluate a resistive heating system, we have to decide between the use of external resistor elements, or the use of the material itself as a resistor element. Using the material as the resistor element has many advantages — the heat appears directly in the material (with little if any transfer losses), and there is no time lag between current flow and specimen heating. The disadvantages are that the current must be well controlled, contact resistance will vary greatly, and material property variables will affect the heating. A far greater range in voltage than 0 to 28 volts would be desirable. Also, the ability to limit the areas to be heated is dependent upon the ability to limit or restrict the areas in which the current flows. Using an external resistor removes almost all of these disadvantages. The resistance can be designed to almost any desired value to meet the voltage and energy requirements. It is a fixed, controlled resistance and not affected by material variables. The heat can be applied in almost any geometric pattern desired. For these reasons, the use of external resistance elements was chosen.

Preliminary analysis of the resistive heating approach showed that the largest energy factor was the energy required to raise the temperature of the material to its forming

temperature. Theoretically, if only one section of the material at a time were heated, and the heat used to soften it were then extracted and moved to the next section to be formed, the total direct energy required would be very small. The ability to "pulse" a heat wave through the material, with all forming action occurring within that heat pulse, is another way of accomplishing this, but it is not a reasonable possibility with today's technology. In this study, it was assumed that the heating of each section would be accomplished directly, and no heat transfer or recovery system would be used.

This study, therefore, took the following approach: The rate of application of energy required to heat the material was calculated. From this, the power leads and the heat transfer mode, i.e., conduction or radiation, into the specimen were evaluated. With these determinations, approximate losses were calculated. The losses plus the heating power required, with appropriate iterations where necessary, scoped the final required design energy rate for forming the cap section.

These were as follows:

Energy Use	Energy Requirement (watts)	
	Contact Transfer	Radiation Transfer
Heating of Material	464	464
Resistive Losses	9	9
Power Lead Conduction	28	28
Reflector Losses	—	30
Other losses (est.)	<u>29</u>	<u>9</u>
	530	540

For the material being considered, each square centimeter must absorb approximately 32 Joules to reach forming temperature. Means must be established to insure that this is accomplished. For efficiency considerations, the driving force or temperature difference should be small (the lower the temperature of all parts the less are the losses). However, the time available to effect this transfer is limited by the motion of the material. Time must be varied, if necessary, by varying the length over which the heat input occurs. Therefore, a proper compromise between temperature differences and area of input must be established.

Another consideration, however, is involved in this particular case. Due to the manufacturing process, the motion of the material will be in 1.434 meter steps, with waiting periods between motions. Because of this manufacturing requirement, heat application can, to some extent, capitalize upon this factor by using a stationary heating surface that contacts the specimen when it is not moving, and by heating an area equivalent to the amount moved in each incremental step. Alternatively, radiant heating may be

applied continuously, smoothing out energy demand. Specifically, the material will be stationary for 40 seconds, then moved at a rate of 2.2m per minute for 40 seconds for a distance of 1.434m, then the cycle is repeated. Thus, a contact heat transfer system could be designed to put heat into the material for approximately 40 seconds out of every 80 seconds. During the 40 seconds of heat input, the input rate must be twice as great as normal. This can be done in two ways. The heating current can be doubled during the heating period and then turned off during the non-heating time. (This would double the resistive losses because they would increase by a factor of 4, being proportional to the current squared, but would occur only over half the time.) Another way would be to let the current remain at the average rate, and have the heat capacity of the material that forms the heating surface absorb this energy during the time that there is no contact with the specimen. This means that the temperature of the heater would rise during this time. Then, when contact was made during the next heating cycle, the total desired energy would be transferred into the material. For radiation transfer equal energy would be transmitted to the laminate during the two periods.

2.2.5 FORMING METHODS. When heated to forming temperature the graphite/poly-sulfone composite attains the overall consistency of wet cardboard. Hence the forming force and power requirements are low. Because softening is restricted to the section fold zones the forming action will be self-centering on the strip. Alternatives for forming the desired section include the use of progressive roller stations, fixed guideways to direct the laminate path-bearing on the unsoftened portions of the strip, and matched forming tools between which the strip passes.

2.3 FEASIBILITY ASSESSMENT

For each of the major fabrication machine operational functions, the requirements and alternative approaches were evaluated in order to arrive at a recommended design solution selection with supporting rationale. These selections were then carried forward to the conceptual design tasks of the flight experiment and the ground-based machine.

2.3.1 HEATING METHODS.

Objective

Determine the optimum material heating method for a selected graphite thermoplastic strip material.

Requirements

Specific derived requirements are:

1. Raise material temperature to 490K (425F) average in affected zones.
2. Do not damage laminate properties.

3. Maximize electro-thermal conversion efficiency.
4. Avoid harmful environmental effects in Orbiter cargo bay.

Alternative Approaches

Energy sources considered were:

1. Electrical Energy (Shuttle Supply)
2. Solar Energy (Direct)
3. Chemical Energy (Exotherm)

Solar and chemical energy sources were rejected on the various individual and combined grounds of cost, complexity, contamination, and state-of-the-art/technical risk. Electrical energy was selected on grounds of availability, cleanliness, and state-of-the-art conversion to heat.

Energy conversion methods considered were:

1. Radiofrequency heating
2. Microwave heating
3. Induction heating
4. Resistance heating
5. Ultrasonic heating

Table 2-6 shows the primary factors of comparison for these methods. Figure 2-7 plots gross electrical power requirement for each method as a function of length of truss (average) formed per second.

Table 2-6. Electrothermal Energy Conversion Methods Comparison

Conversion Method	FACTORS OF COMPARISON					Critical Issues/Risks
	Energy Transfer Mechanism	Characteristic Frequency	Power Conversion Method/Efficiency	Heat Transfer Efficiency	Overall Efficiency	
RF Heating	Matrix heating by dielectric losses	2.8 GHz	DC-DC DC-RF ~ 32%	100%	32%	Shielding for EMC
Microwave Heating	Absorption of microwaves by matrix	2.8 GHz	DC-DC Magnetron ~ 48%	100%	48%	Shielding for EMC
Induction Heating	Fiber heating by eddy current losses	24 MHz	DC-DC DC-HF < 40%	100%	40%	Insulated directional graphite fibers suppress eddy currents
Resistance Heating	Radiant or conductive heat transfer to outer surface	DC	Resistive Element ~ 100%	Radiant ~ 94%	94%	Reflector cooling
				Conductive ~ 100%	~ 97%	Contact resistance. Stick-ing platens Delayed start-up
Ultrasonic Heating	Frictional heating of material	20 KHz	Resonant Horn TBD %	~ 100%	TBD	Tool wear Tool compliance Auxiliary heating

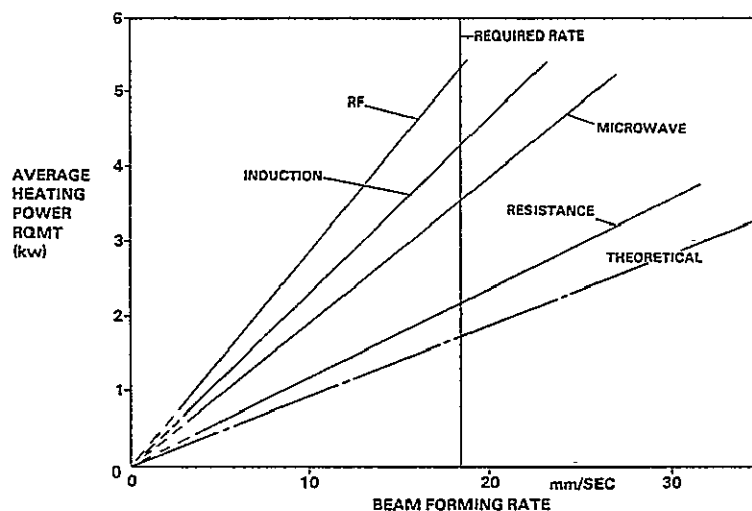


Figure 2-7. Electrical Power Requirements as a Function of Heating Method and Forming Rate

Evaluation

Analysis has shown and test has corroborated that RF, microwave, and induction heating are inefficient for the heating of GTP strip due to the power conversion requirements from 28 VDC.

Resistance heating has been demonstrated as a satisfactory process by analysis and bread-boarding. Application may be by radiant energy (Figure 2-8) or surface conduction through a platen (Figure 2-9) depending on design considerations. Table 2-7 shows the major advantages and disadvantages of each method.

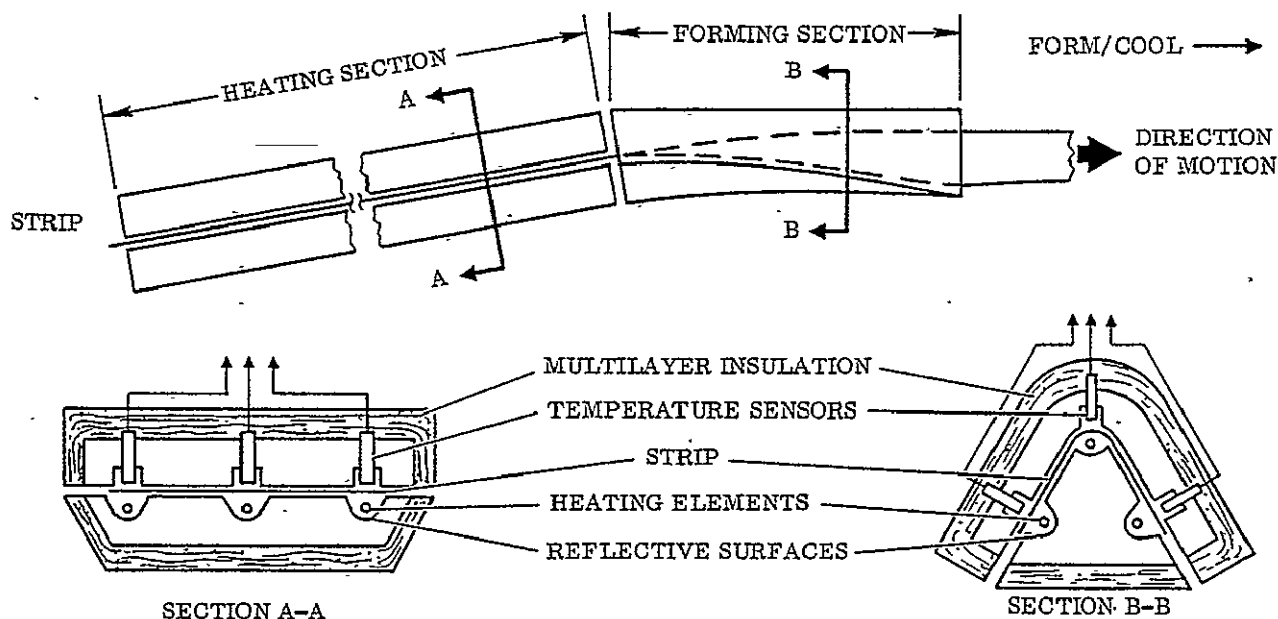


Figure 2-8. Heating Arrangements - Radiant Transfer

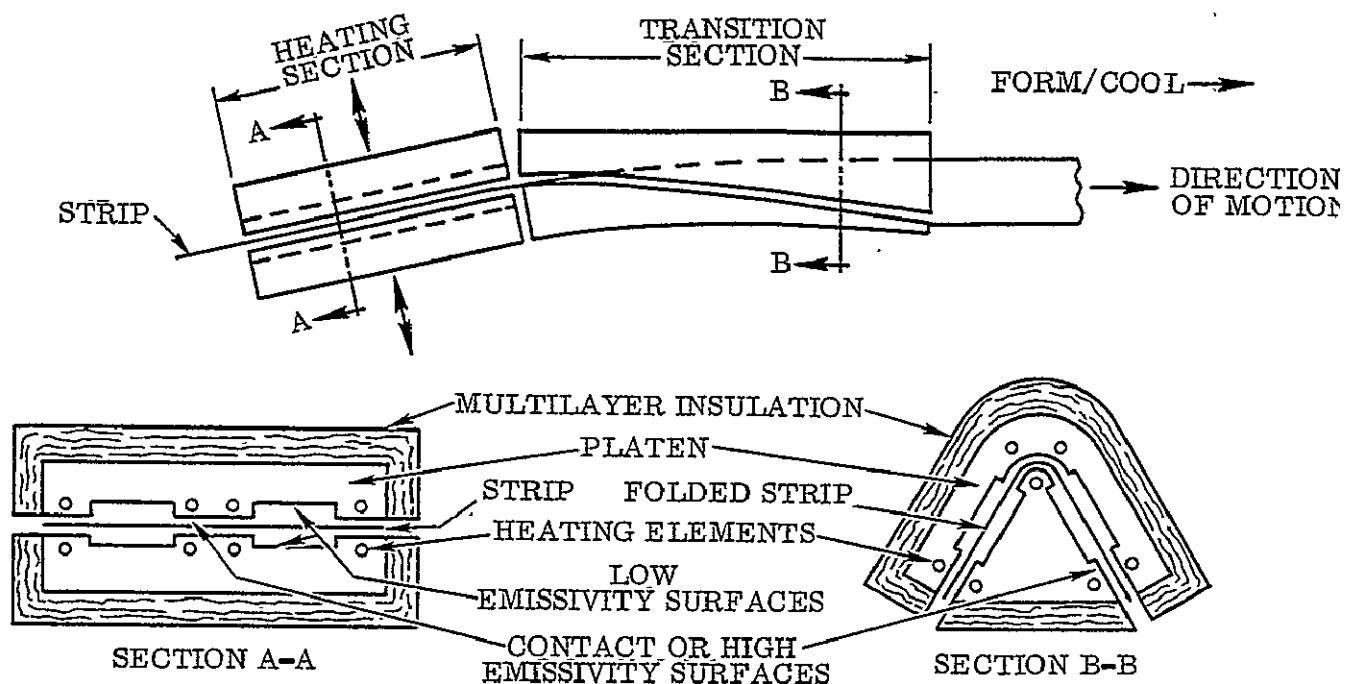


Figure 2-9. Heating Arrangements - Conduction Transfer

Table 2-7. Application of Resistance Generated Heat - Comparison of Methods

Factor	Radiant Heating of Surfaces	Contact Heating of Surfaces
Predictability of Heat Transfer	Good	Wide variation of contact resistance in vacuum
Conditions of Heat Transfer	Stationary and Moving Surface	Stationary Surface Only
Thermal Inertia	Low	High
Control Response	Fast - Measures Material Temp.	Slow - Measures Platen Temp.
Element Temperature	800 - 950 K	> 625 K (Breakdown Temp 640 K)
Thermal Losses	Low	Very Low
Vulnerability	Low - Calrods	Low - Calrods in Platen
Complexity/Reliability	One Side Heating - No Moving Pts.	Two Sides Heating with Moving Platens
Contact with Adhesive Surface	No Contact	Large Area Contact under Pressure
Problem Areas	Reflector Cooling	Thermal Warpage of Platens Potential Overheating Material
Relative Cost	1.0-	> 1.0 Linkage Motion & Control

Resistance heating by passing current directly through the carbon filaments of the material was considered. However, no way of making the necessary electrical connections could be devised without damaging the laminate.

Ultrasonic surface heating has been demonstrated as a feasible technique. There are practical problems involved in transferring the energy as heat to the strip at adequate density to achieve the desired temperatures. Heating by ultrasonics in the form transition area at start-up or during pause would be difficult or impracticable.

Recommended Selection and Rationale

The use of electrical resistance heating is recommended on the grounds of lowest relative cost, highest reliability, minimum risk and flexibility of application.

The recommended energy transfer mechanism is radiation from rod heaters. The radiation is directed at the fold areas to be heated, the other areas being masked. This method will be used for primary operational heating, auxiliary start-up heating, and temperature maintenance. Figure 2-8 illustrates the general arrangement. Figure 2-10 gives parametric design data for the heater elements.

Radiant rather than conduction heat transfer was selected for better predictability and control of energy transfer, avoidance of moving parts, operability on both moving and stationary strip material, and avoidance of contact with hot plastic adhesive surfaces.

2.3.2 FORMING METHODS.

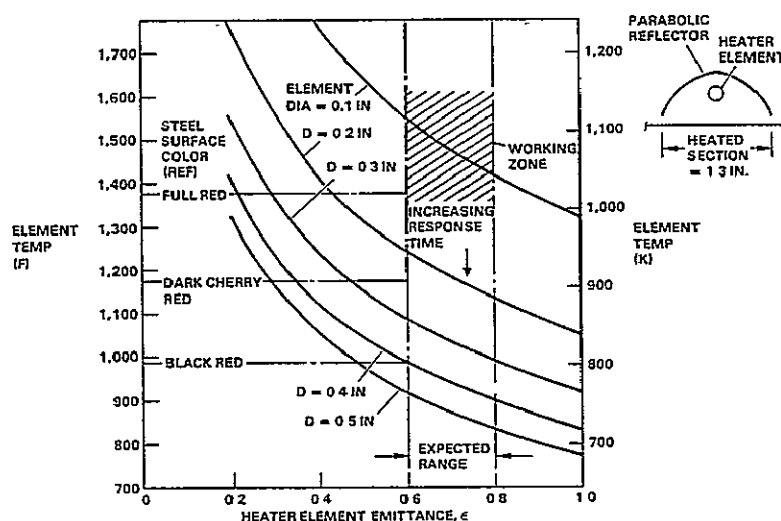


Figure 2-10. Heater Element Parametric Design Data

Objective

Determine the optimum material forming method for a selected graphite thermoplastic strip material.

Requirements

Specific requirements are:

1. Form material to the sections shown in Figures 2-11 and 2-12 from flat strip stock.
2. Avoid wrinkling or collapse of heated strip.
3. Avoid delamination of heated material.
4. Avoid resin pickup from material surface.

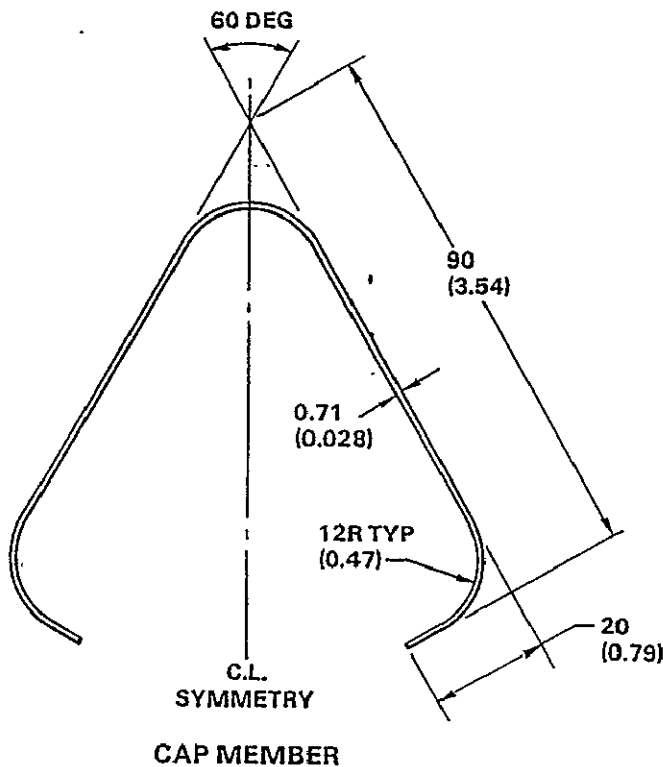


Figure 2-11. Beam Cap Cross Section

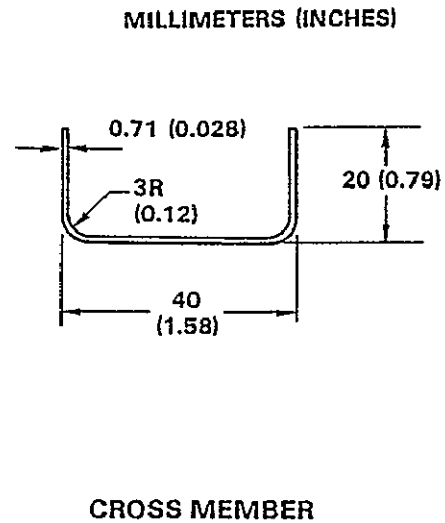


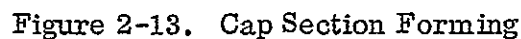
Figure 2-12. Cross Member Cross Section

5. Minimize localized conductive heat loss.
6. Material strip must run true within ± 3 mm.
7. Auxiliary heating must be incorporated for start-up.

Alternative Approaches

Consider the cap section, Figure 2-11. The bend zones are heated to softening while the strip is flat. The strip is drawn up to a final roll forming station and subsequently cooled. In the transition from flat stock to fully formed section the following factors are of design importance.

1. Fiber content of the laminate has zero plasticity at any time and hence longitudinal element paths are uniquely defined by the start and finish section shapes. Correct inflow angle α must be determined and used (Figure 2-13).
2. Section change approximates two flat strips in helical winding with one pair of edges joined. Tension forces and compression displacements exist sequentially at the central fold area.
3. Owing to the helical path assumed by the strip edges, turn-down of the edge flanges must be performed after center angle forming is complete to avoid crippling and potential fiber damage.



- Figure 2-13 illustrates the cap section progress through transition. Between sections A and C the central fold area is in tension. After the inflection point the central fold area is in compression as shown in section D where displacements are accommodated by center area distortion. At E the full angle form is set and the flanges turned by F. The full section goes on to cooling and form setting.

1. Rollers
2. Fixed guideways
3. Matched forming tools

Form rollers with a matched gap equal to material thickness shape the material at selected locations. There is some surface scrubbing due to varying roller radius at constant strip linear speed. There is room between rollers for auxiliary heaters. The rollers require high temperature bearings and a non-stick surface.

Fixed guideways scrub the surface of the strip at linear speed. Contact pressure will be low. Surface must be sufficiently non-stick to prevent scraping off of resin. Auxiliary heaters may be installed between guides.

Matched forming tools constitute a small gap continuous guideway with integral auxiliary heating strips.

Tracking and alignment of the moving strip cannot be achieved by edge guiding. The non-yielding nature of the laminate voids classical planar action control by crowned rolls. However, the collimated character of the unidirectional graphite fibers combined with selective softening of the bend areas only, assures accurate straight line tracking.

Evaluation

Roller forming has been successfully breadboarded and used in the rolltrusion machine. Use of guideways in a supplemental control mode with low bearing pressures is practical.

Recommended Selection and Rationale

Roller forming with auxiliary guideways (fairleads) is recommended. Rollers assure good shape and redress of local abnormalities if they occur. Guideways constrain flat areas.

2.3.3 COOLING METHODS.

Objective

Determine the optimum material post-forming cooling method for GTP structural sections.

Requirements

Specific requirements are:

1. Cool material to below 422K (300F) ($T_G = 464K (373F)$).
2. Assure dimensional integrity of section during cooling.
3. Assure laminate integrity during cooling.

Alternative Approaches

Cooling methods considered were:

1. Conduction to a cold plate
2. Radiation to a cold wall or space
3. Convection by gaseous impingement
4. Evaporation by liquid impingement

Convection and evaporation (ideal earth-bound methods) were rejected for logistics reasons in a downstream application.

Radiation cooling was analyzed for heat rejection to a cryogenically cooled cold box, and to space with variable view factor representing obstructions. The results are shown in Figures 2-14 and 2-15. In each case a nominal cooling time of about 40 seconds is indicated and this is compatible with fabrication machine timelines under consideration.

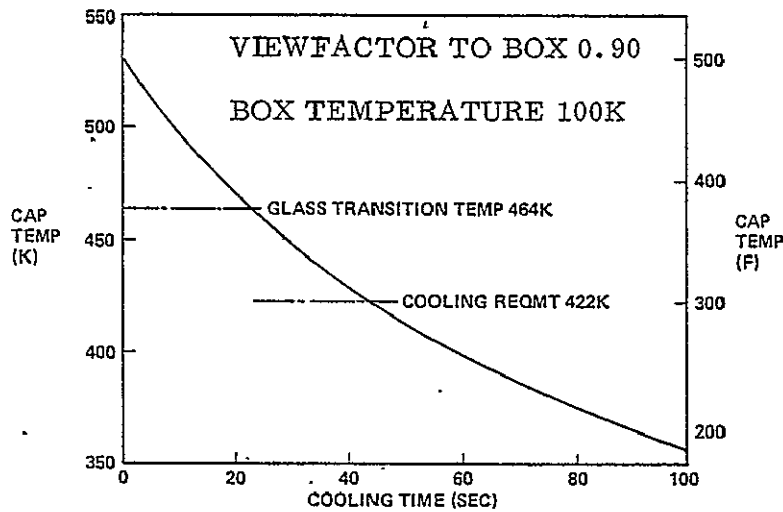


Figure 2-14. Cap Temperature - Cooling to Cold-Box

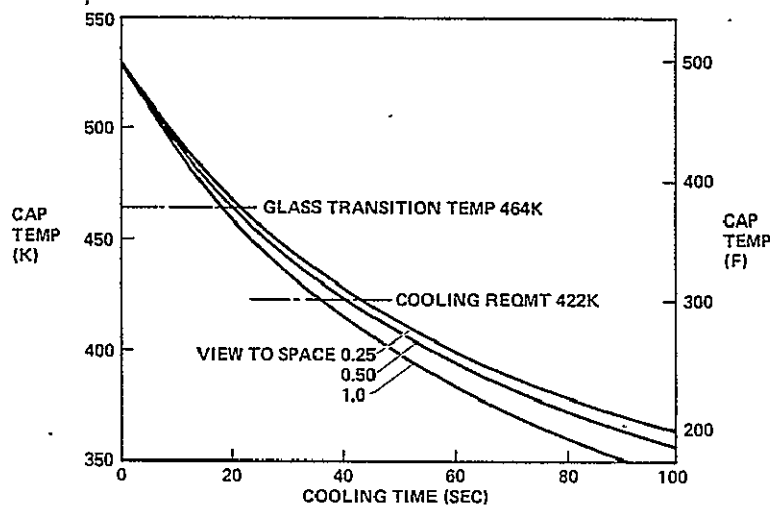


Figure 2-15. Cap Temperature - Cooling to Space

To achieve close control of final section form after cooling without unduly restricting radiation cooling an open mesh form tool would be required. Its use would increase cooling times and likely leave a waffle pattern on the laminate.

Conduction cooling was analyzed with the formed section held in contact with a liquid cooled form tool or platen. See Figure 2-16. For a mean platen temperature of 290K the cooling requirement is met in 22 seconds with the removal of ~50 kilojoules of heat. After 40 seconds of cooling a low temperature of 366K (198F) is achieved. A realistic contact conductance (under hard vacuum conditions) of $28 \text{ Wm}^{-2}\text{K}^{-1}$ ($5 \text{ BTU hr}^{-1} \text{ ft}^{-2}\text{F}^{-1}$) between platen and graphite/thermoplastic material was used. With platen cooling the formed section can be held to final shape by matched platens or a single platen with a resilient pressure member. Laboratory tests have shown no tendency for the cooled laminate to stick to the platen.

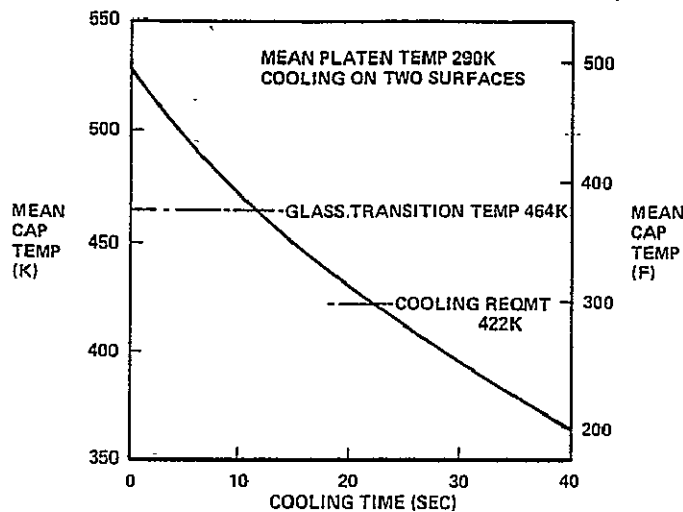


Figure 2-16. Cap Temperature - Conduction Cooling

Evaluation

Both radiation and conduction cooling provide adequate thermal performance to meet machine requirements. The cold box refrigeration presents logistic and operational difficulties. Conduction cooling has the greater performance margin to cover variations in contact resistance and greater machine operating speeds for growth development.

In meeting the requirements for dimensional and laminate post-forming integrity the cold platen with matching or conforming pressure member is superior.

Recommended Selection and Rationale

The use of conduction cooling through a platen is recommended because of superior performance in meeting requirements. Platen cooling can be adequately maintained by heat exchange to the Orbiter payload support system. Extracted heat may be considered for use in pre-warming strip stock to effect an energy consumption economy and provide a margin on Orbiter 6.3 KW (thermal) payload cooling support.

2.3.4 JOINING METHODS

Objective

Determine the optimum joining method for beam assembly of rolltrusion produced members.

Requirements

Specific requirements for the cap to cross member joint are:

1. Cross member axial load 470 N (106 lb) limit
2. Adaptable to beam configuration changes
3. Able to trap and hold diagonal bracing cords

Alternative Approaches

Joining methods considered were:

1. Ultrasonic heat welding
2. Direct heat welding
3. Adhesive bonding

Evaluation

Ultrasonic welding of a flat or dimpled spot is accomplished in a fraction of a second at moderate pressure on the faying surfaces. The polysulfone film on each surface is melted by frictional heat and fuses. Weld cooling to below fluid temperature is almost instantaneous by conduction into the material. For a dimpled spotweld about 10 mm in diameter a shear strength of well above 2000 N has been demonstrated. Joint design using three dimpled welds and capturing a polysulfone-impregnated S-glass roving bracing cord is a practically demonstrated approach.

Direct heat welding provides satisfactory attachment at lower energy efficiency due to losses and active cooling required. It is also slower.

Adhesive bonding is a well established technique which takes advantage of the full area of the faying surfaces. Bond setup time and potential outgassing are process problems.

Recommended Selection and Rationale

Ultrasonic welding is recommended as the basic joining technique for graphite, polysulfone structural members. This method is rapid, economical of energy, contamination free, and proven. The 20 kHz sonic energy is transmitted by metallic probes and is not affected by vacuum operating conditions.

2.3.5 CUTTING METHODS.

Objective

Determine the optimum cutting method for severing cap and cross members to length.

Requirements

Specific requirements are:

1. No debris must be released
2. No splitting, delamination, cracking of the cut edge

Alternative Approaches

Cutting methods considered were:

1. Shearing
2. Sawing
3. Laser cutting

Evaluation

Sawing and laser cutting cause free debris and contaminating process products, and hence do not meet requirements.

Shearing tests on flat strip give clean, debris-free cuts, with clean edges. However, tool design to give a clean cut on open triangle and channel sections has yet to be developed.

Recommended Selection and Rationale

Cutting by shearing is the recommended selection. The method is potentially debris free, energy economical, and long life.

SECTION 3

FLIGHT EXPERIMENT

The primary objectives of the flight experiment are fabrication of a typical large space structures beam using experimental equipment mounted on a Space Shuttle pallet, monitoring of the fabrication process and its control for fabrication capability assessment, evaluation of the erected beam's response to dynamic excitation and varying thermal exposure, and return of the beam or a portion of it to the ground for examination.

Structures fabrication capability in space will eventually be achieved in a number of discrete steps. Typically these may be:

1. Design, construction, and test evaluation of a ground-based fabricator unit to explore process variables and alternatives, demonstrating the capability of a selected fabricator design within the constraints of terrestrial simulated space environment.
2. Development of a Space Shuttle Orbiter-based fabrication facility for demonstration of orbital fabrication capability for basic space structures beams.
3. Development of space-based, free-flying construction facilities with Orbiter resupply capability for erection of large space structures arrays.
4. Eventual development of space-based construction facilities for very large space systems with reusable heavy-lift space transporter resupply.

Since first-generation large space structures must support the technology for final very large systems, fabrication techniques employed for the first large space structures generation should be fully applicable to construction of final systems. Prototype systems will need to be deployed before national commitments to very large future systems can be expected.

Space Shuttle will serve as a vital link to all future large space structures and systems development. Technology development can be pursued using Space Shuttle Orbiter capabilities to the fullest.

This study provided for conceptual design of the flight experiment to assure that the preliminary design of the on-ground demonstration machine is soundly based for future flight development.

3.1 CONCEPTUAL DESIGN

The conceptual design of a flight version fabrication machine provides the basis for conceptual design of the flight experiments to be conducted with it.

3.1.1 MACHINE DESCRIPTION. The beam fabricator feeds and processes raw materials in the form of coiled graphite polysulfone laminate strip and polysulfone impregnated S-glass roving cord into a completed continuous braced triangular cross section beam of one meter depth. New technology in the roll-trusion hot forming of structural sections is combined with state-of-the-art mechanical and electrical/electronic design practices to effect straightforward flightweight product. Through an iterative design and trade study development approach the machine shown in general arrangement in Figure 3-1 has been evolved.

3.1.1.1 Rolltruder Unit. Graphite thermoplastic (GTP) laminate strip which has been produced on earth in flat, fully processed condition is stored by prewinding on reels. Each of the six reels is enclosed in a can and has a drag axle as a hold-back against premature uncoiling and to retain the strip in tension as it passes through the forming process. After being drawn from the reel the GTP strip passes through a heating section. In this unit the strip is progressively heated to softening temperature in the structural shape bend zones only for energy economy. The heat is applied by radiant elements backed up by parabolic reflectors. When the strip passes from the heating into the forming section it is sequentially roller formed to shape. After forming each formed shape is cooled between platens which close and assure post-forming laminate and dimensional integrity. (Assembly operations take place downstream in the machine during this pause.) The formed strip is gripped by driving rollers situated immediately after the cooling platen installation. Drives for the three cap sections are synchronized by connecting torque shafts. A differential gearing system assures equal feed rates at each cap. Provisions for active differential drive are made but not implemented pending a demonstrated need revealed by development testing. Each cross member section is driven independently into the transfer mechanism receptacle and then sheared to length.

3.1.1.2 Assembly Unit. The assembly unit strings the diagonal bracing cords into position, places a cross member in position on each of the beam's three sides to trap the cords between itself and the cap members at each end and then ultrasonically welds the complete joint at each end of the three crossmembers.

Cord stringing is done by three pairs of contra-rotating concentric "windshield wiper" arms pivoted at the centerline of each side of the beam. Cord is fed from reels near the pivot, along the arms and out of bell-mouthed stingers in the face planes of the beam. The arms incorporate a preset cord tensioning device.

The cross member transfer mechanism raises and then rotates the part ninety degrees, passing above the cords. It is then pressed down into the welding position by the weld heads. An ultrasonic weld head at each joint makes three spot welds which trap the cord in place and effectively brace each bay.

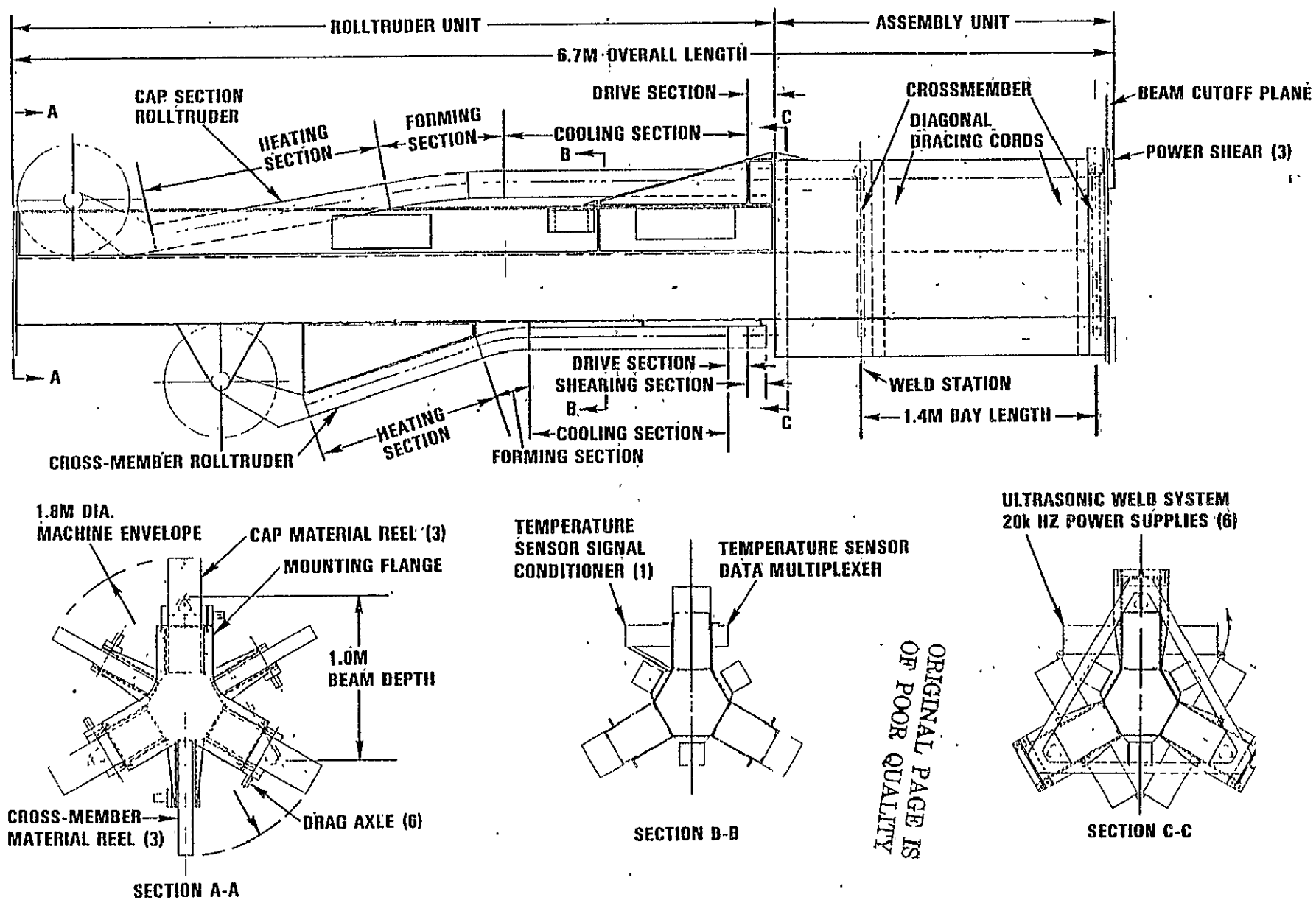


Figure 3-1. Beam Fabricator General Arrangement

Power shears at the end of the machine sever cap sections and cords when the beam fabrication is complete.

3.1.1.3 Structural Support. A lightweight hexagonal box section spine runs the length of the machine. This structural member carries machine mounting provisions, the modular rolltrusion units, the assembly mechanisms, and the electrical/electronic control gear. It forms a rigid base for weld head and shearing anvils. It cantilevers the close profile triangular casing for the assembly unit. It is designed to maximize accessibility for ground maintenance and assembly.

3.1.1.4 Control System. Temperature sensing of GTP material in the heating and forming sections of the machine is done by infrared sensors. The heater elements are driven by a 28 VDC source through system processor controlled switches giving an on-off energizing mode. Switch actuation is based on data provided by the temperature sensors and the selected mode of machine operation. The cooling platen, drive motor, and assembly operation sequences are also controlled by the system processor. A data multiplexer provides signal conditioning outputs to the processor via a data bus. The processor control bus interfaces with each of the functional areas via device-peculiar interface units. The processor interface with the orbiter mission specialists station allows operator monitoring and activity update of the system.

3.1.2 SHUTTLE INSTALLATION. Figure 3-2 depicts the beam fabricator installed in the Orbiter payload bay. The maximum beam fabricator envelope dimensions (excluding the trunnion mount) are 2.30 m dia. and 6.71 m long. The beam fabricator is installed on a two segment pallet train using a trunnion attachment aft and saddle attachment forward. The trunnion also provides for deploying the machine to a vertical position in the payload bay for fabricator operations or test. The installed payload length is 9 m including overhang beyond the pallet and clearance for deployment. Locks are provided to secure the beam fabricator to the pallet during launch and landing.

Standard Spacelab pallet segments provide structural mounting hardpoints for the beam fabricator. Other payload equipment may use inner skin mounting. Spacelab pallet equipment such as electrical power distribution, cold plates, igloo and igloo mounted subsystems (e.g., computer) are not required. LSSFE equipment hardware interfaces with Orbiter provided resources as follows:

Power - Sta X₀ 695, AFD and at Pallet I/F

Signal/Control - Sta X₀ 576, AFD and at Pallet I/F

Payload Heat Exchanger - Supply/Return Sta X₀ 636, and at Pallet I/F

RMS - Grapple Device and End Effector

Payload equipment located at the AFD Payload Station includes fabricator operational and test controls and displays, vibration exciter system and analysis C&D, thermal

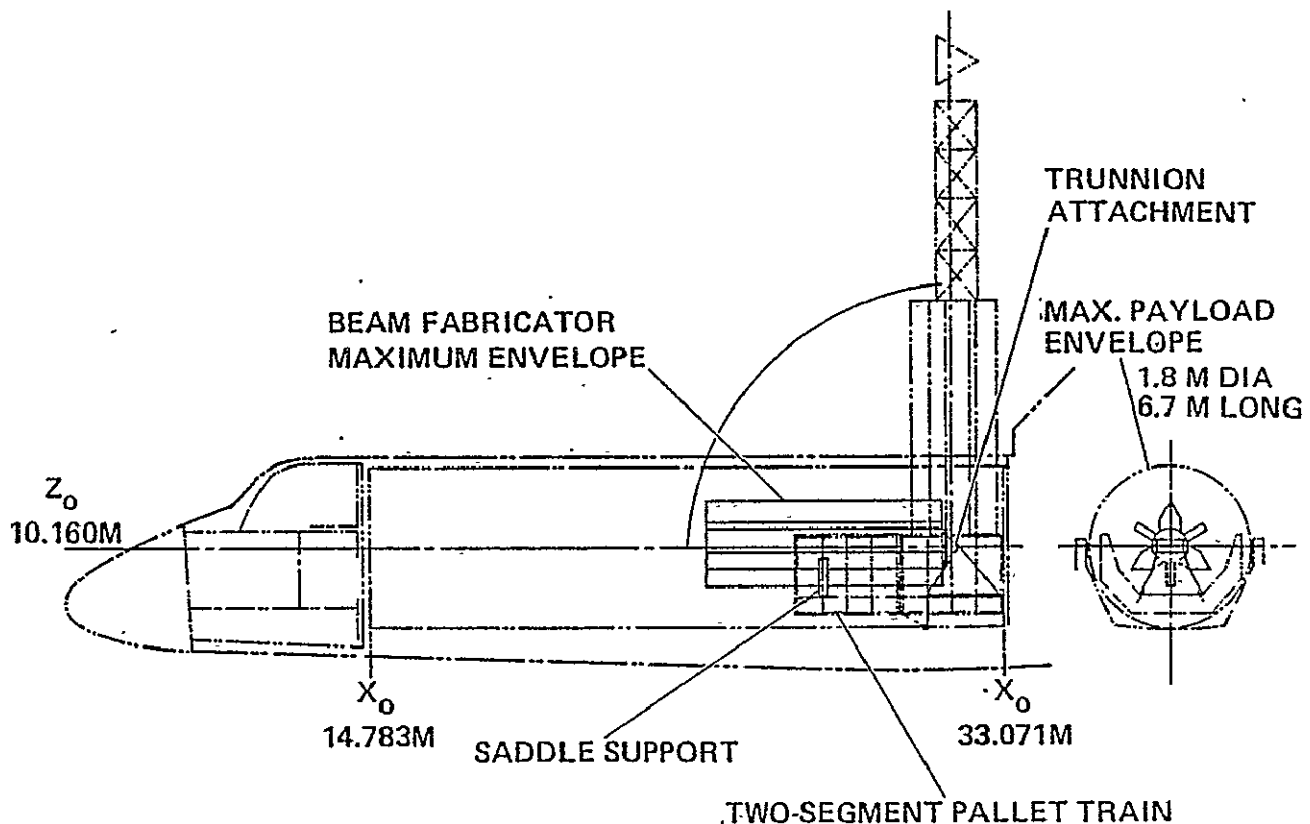


Figure 3-2. Shuttle Installation of Beam Fabricator

test/sunshade control and displays and instrumentation system controls. At the On-Orbit Station are payload provided controls for fabricator erection, launch locks, CCTV monitor switching, CCTV cameras, and returned beam stowage devices. Payload caution and warning is installed at the Mission Station.

The on-orbit fabrication flight experiment can be accomplished using one Shuttle flight. Since the experiment equipment to be delivered and returned by the Shuttle from a low earth orbit uses only a portion of the weight and length available to payloads, it is highly desirable that the flight experiment shares the Shuttle flight to reduce user charges. The experiment and its support equipment will be designed to use approximately one-half of the Orbiter payload bay length. The experiment equipment will mount on a Spacelab pallet consisting of two standard 3-meter segments joined to form a pallet train.

Operational flexibility, in terms of the potential for LSSFE equipment to share the Orbiter payload bay with a variety of payload classes or types, is shown in Figure 3-3. For example, a short Spacelab module mounted at Orbiter longeron attach points 801.53" and 895.93" will provide clearance for all planned payload/RMS operations. Visibility from the aft flight deck (AFD) windows into the bay will be restricted in this configuration.

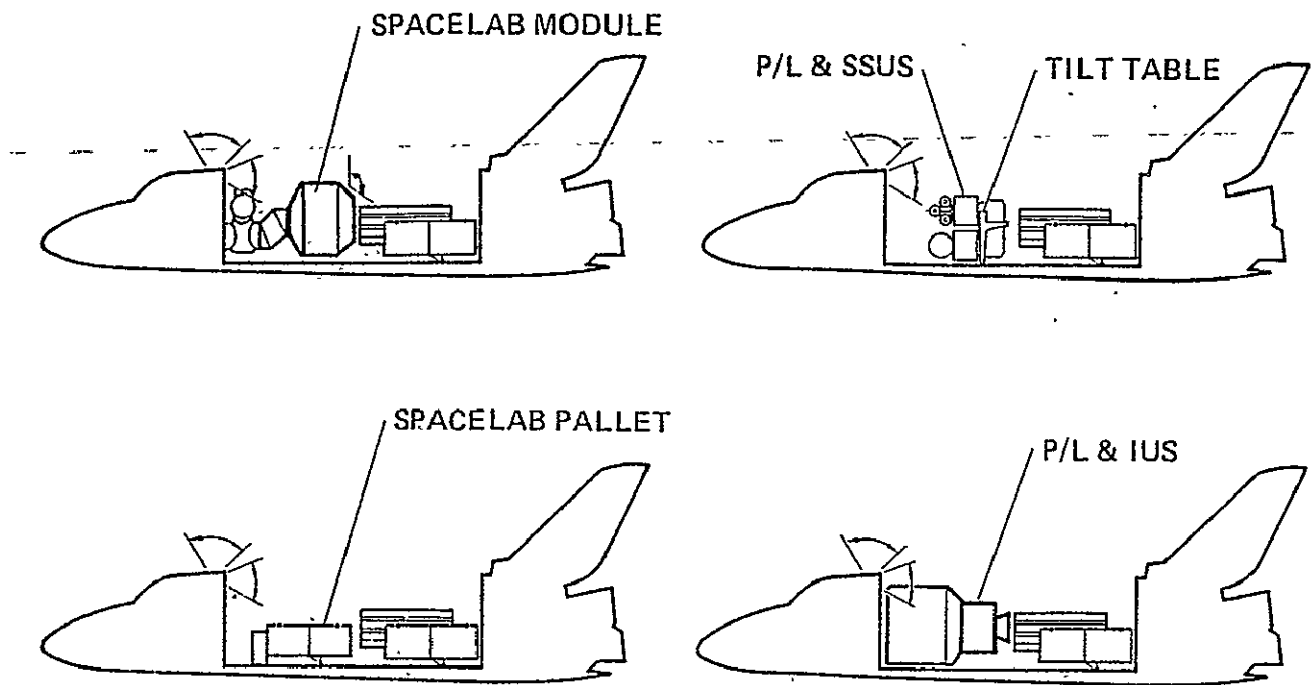


Figure 3-3. Shuttle Mission Sharing Capability

However, equivalent viewing is provided through a viewpoint with a 120° field of view (FOV) located in the module aft cone. Spacelab pallet-only payloads can also potentially share flights with the LSSFE. Integration of payload AFD accommodation requirements will need special consideration.

The LSSFE is a potential co-passenger for upper stage delivered payloads within Orbiter weight and c.g. limitations. Upper stage airborne support equipment remaining in the payload bay, e.g., tilt table, do not appear to constrain planned experimental activities, and typical upper stage delivery mission timelines are compatible with LSSFE operations. Baseline operational procedures provide for cutting the 100 meter (100 Kg) experimental beam into lengths for return rather than jettisoning it. Specific return packaging will be dependent on the companion payload equipment remaining in the cargo bay. A maximum of thirteen lengths can be carried back cordwood style attached to the final nine meters of beam protruding from the fabrication machine. In addition two lengths can be stored top-side to the machine casing. Support requirements for the lightweight beam sections during orbiter return will be met by damped resilient constraints.

3.1.3 THERMAL ANALYSIS. The feasibility assessment given in Section 2 selected radiant resistance heating as the preferred heat transfer mechanism to GTP strip. The thermal analysis of this arrangement is as follows:

Objectives

1. Determine the amount of energy necessary to bring the graphite thermoplastic material from 255 K (0 F) up to a required temperature of 490 ± 15 K (425 ± 25 F) (transition temperature = 464 K (325 F)) in the heating section and maintain this temperature in the forming section for a 40 second run, 40 second pause machine operation.
2. Calculate the required mass flow rate of coolant needed to bring the graphite strip below the transition temperature in the cooling section, and remove the energy accumulation in the reflectors of both the heating and forming sections.
3. Determine a workable method that will give a proper temperature distribution along the heating and forming sections at startup.

Assumptions

1. Initial material temperature is 255 K (0 F).
2. Final material temperature in cooling section must be at most 422 K (300 F).
3. Of the total energy emitted by all heating elements, 6% is absorbed by the reflectors while the rest is absorbed in the graphite thermoplastic material.
4. Strip thermal conductivity varies linearly with temperature as follows:

	Btu/hr-ft-F		Watts/cm-K	
	Length	Direction	Length	Direction
Length	16 at 260 R	52.7 at 590 R	.277 at 144.4 K	.912 at 328 K
Direction				
Transverse	.333 at 200 R	.666 at 590 R	.0057 at 111.1 K	.0125 at 328 K
Thickness	.333 at 200 R	.666 at 590 R	.0057 at 111.1 K	.0125 at 328 K

5. Specific heat varies linearly with temperature as follows:

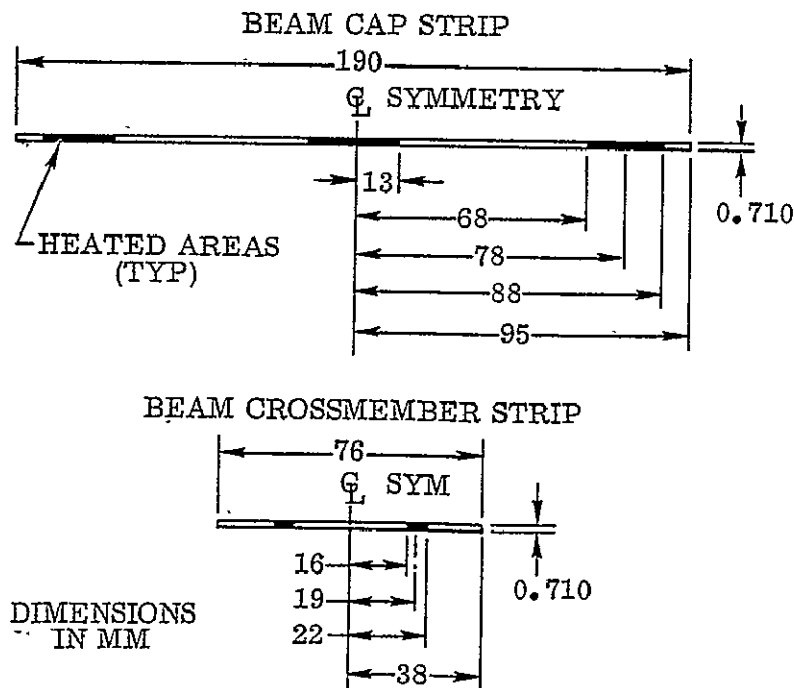
C_p , Btu/lb-F	C_p , joule/kg-K
.10 at 260 R	418 at 144.4 K
.30 at 760 R	1256 at 422.2 K

Discussion

Heating Analysis — Detailed computer models were set up to simulate the 40 second run, 40 second pause machine operation for both the caps and cross members. For one cap and cross member, the length of strip modeled was the heating section length plus 30.5 cm at each end to account for axial conduction out of the heating section. A 204.5 cm length of one symmetrical half of the cap strip was subdivided into 20 longitudinal nodes x 6 transverse nodes. A 197.8 cm length of one symmetrical half of the cross member strip was subdivided into 18 longitudinal nodes x 5 transverse nodes.

Heat is applied only to the areas of strip that are to be bent in the forming section. These areas are shaded in Figure 3-4. The heating history of each heated longitudinal node represents movement of the strip into the heating section in 40 seconds, followed by 40 seconds of heating while stationary. Heat input to the strip was adjusted to give the desired temperature at the entrance to the forming section at the end of the 40 second pause.

Extremely high temperature gradients occur across the width of the strip (see Figure 3-5). This is due to the low thermal conductivity (mean value = 0.0127 Watts/cm-°K) in the transverse direction and is a desirable condition because it minimizes the total energy input needed to bring the strip up to temperature.



In the heating section, a minimum total of 494 watts is needed for one cap. The cap is heated in three different areas where the center must receive 200 watts with 147 watts needed at each of the edge areas. The area at the center is larger, thereby necessitating the greater energy input in that region.

For one cross member, a total of 114 watts is needed in the heating section. There are two equal areas requiring energy input, with each receiving 57 watts.

Figure 3-4. Cap and Cross Member Strip Cross Sections

Figures 3-6 and 3-7 show the longitudinal temperature distribution along the heated areas of the beam cap and cross member at various time steps. A temperature "ramp" is seen to develop as the strip moves under the heaters during the first 40 seconds. The sloping temperature profile is then raised during the next 40 seconds until at 80 seconds the forward end is at the correct temperature and is ready to move into the forming section.

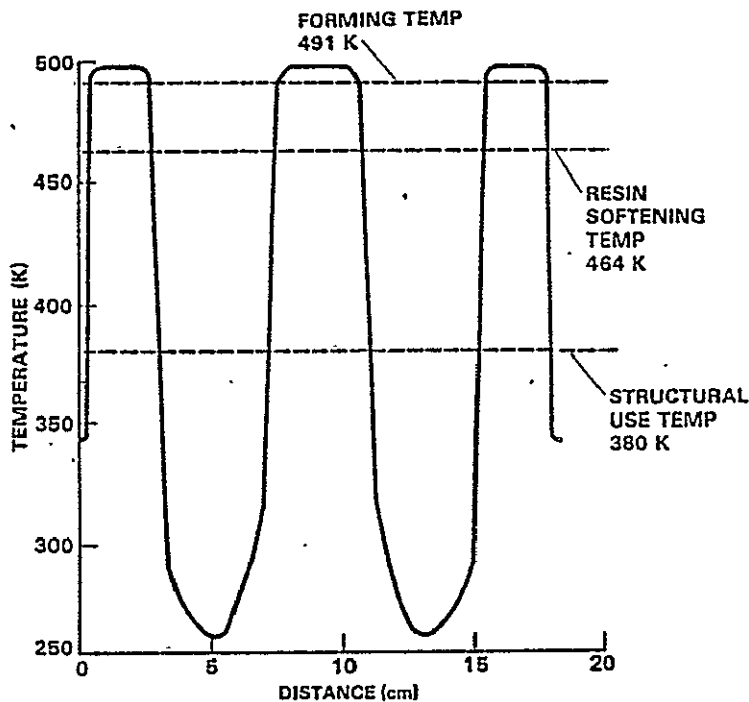


Figure 3-5. Cap Transverse Temperature Distribution at Entrance to Forming Section

In the forming section, one cap will require a minimum of 40 watts to maintain proper temperature. This input is needed to replace (1) energy that is constantly moving transversely across the strip into the colder areas, plus (2) longitudinal losses to the cooling section and areas of the heating section not yet up to temperature. The center area must receive 16 watts while each of the edge areas require 12 watts. One cross member requires 12 watts in the forming section with 6 watts being input at each of the two heating areas.

The assumption was made that 6% of all the energy in both heating and forming sections is absorbed in their reflectors.

Argus International states that 6% reflector absorption is a typical value for focused infrared heating.

Cooling Analysis — The cap and cross member temperatures must be brought down below the transition temperature in the cooling section. This is accomplished by conducting heat into aluminum platens placed against the formed strips during the 40 second pause interval. Freon running through the platens removes this energy. This coolant is also used to remove the energy absorbed in the reflectors of the heating and forming sections.

The total amount of cooling required in the rolltrusion machine will be quite low. For example, approximately 340 watts must be absorbed in the cooling

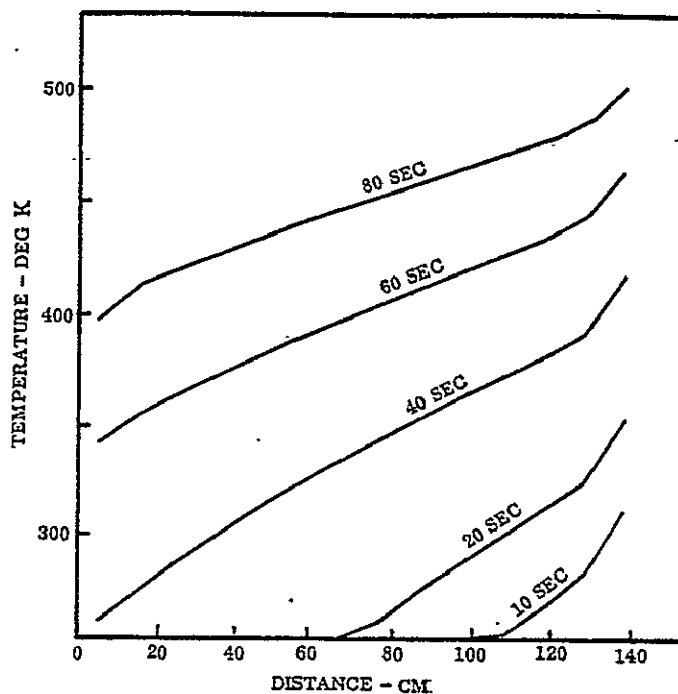


Figure 3-6. Cap Strip Longitudinal Temperature Distribution in Heated Area

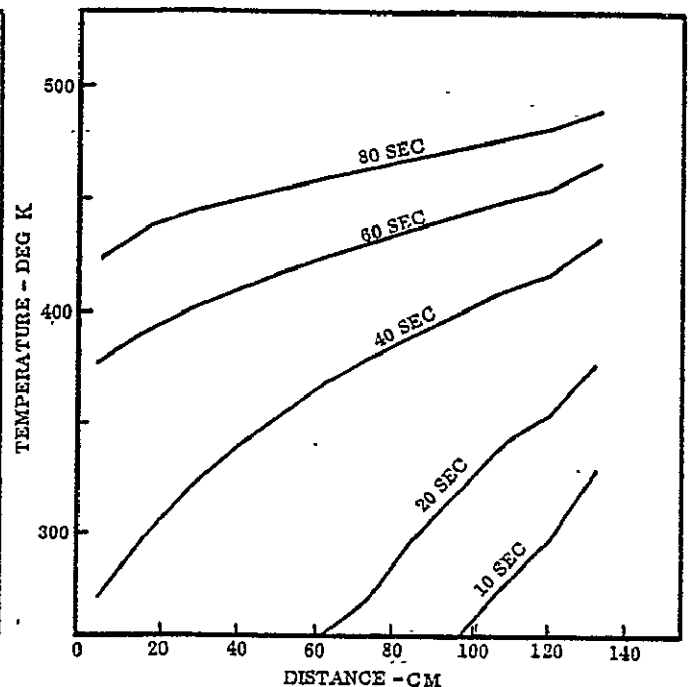


Figure 3-7. Cross Member Longitudinal Temperature Distribution in Heated Area

section from one cap during the pause interval. Using a 0.5 Kg/min mass flow rate for each cap, the coolant temperature would rise approximately 11.0 C (19.5 F). If the same coolant is used to dissipate the energy accumulation in the cap reflectors (approximately 33 watts) an additional increase of 1.2 C (2 F) would occur making a total temperature rise of 12 C (21.5 F). Cooling services provided by the shuttle can supply 907 Kg/hr (2000 lb/hr) of coolant at 280 K (45 F) with a maximum return temperature of 328 K (130 F) if needed. It should be further noted the maximum allowable coolant pressure drop is 310 Torr (6 psi). It is estimated the total pressure drop would be less than 5.17 Torr (0.1 psi) if the coolant flows continuously through heating, forming, and cooling sections.

Start Up — At start up, it is necessary to bring the material temperature up to 490 ± 15 K in the forming section and have a similar temperature distribution along the heating section as exists at every 80 second cycle during normal operation (see Figure 3-6, $t = 80$)..

The major limiting factor in start up is the amount of available power in the forming section. If the minimum value required for normal machine

operation is used, it would take approximately 10-12 minutes to heat the material in the section from 255 K to 490 K.

A total time of 5 minutes has been chosen as a ground rule for start up. Based upon this time, 105 watts must be made available in the forming section for one cap.

A satisfactory temperature distribution in the heating section can be created by placing two separate heating elements end to end within the heating section, and turning each on at different times in the start-up sequence. Figure 3-8 illustrates the heating element configuration, a workable timeline for start up, plus the resulting temperature distribution across the heating and forming sections for one beam cap.

Summary — The results of the thermal analysis show the total minimum power required for normal rolltrusion operation to be approximately 2.0 Kw. This takes into account only the heating and forming of 3 caps and corresponding cross members. It assumes a 6% loss into the heater reflectors but no other losses. The shuttle has the capability of supplying 7 Kw average, 12 Kw peak for not more than 15 minutes. Energy requirements in the heating and forming sections for the beam cap and cross members may be summarized as follows:

	<u>Heating Section</u>	<u>Forming Section</u>	<u>Total (Watts)</u>
Beam Cap	494	40	534
Beam Cross Member	114	12	126
for one Beam = 3 (534 + 126) = 1.98 Kw			

These are minimum total power requirements with no losses except 6% into the heater reflectors.

3.1.4 CONTROL REQUIREMENTS. The system control diagram shown in Figure 3-9 illustrates the control and data requirements for one cap section of the beam fabrication machine. These are typical for each of the three cap sections involved, and representative of the interface functions involved in the cross-member (excluding weld heads) area. The diagram is centered around the processing sequence of the graphite-thermal-plastic (GTP) material, whose flow is indicated by the heavy dashed horizontal line across the center of the page. The following paragraphs define the functional areas indicated.

First shown is the GTP heating section, whose heater elements are shown above the material, and whose infra-red temperature sensors are shown below the material. Next in the sequence is the GTP forming section, with heaters and temperature

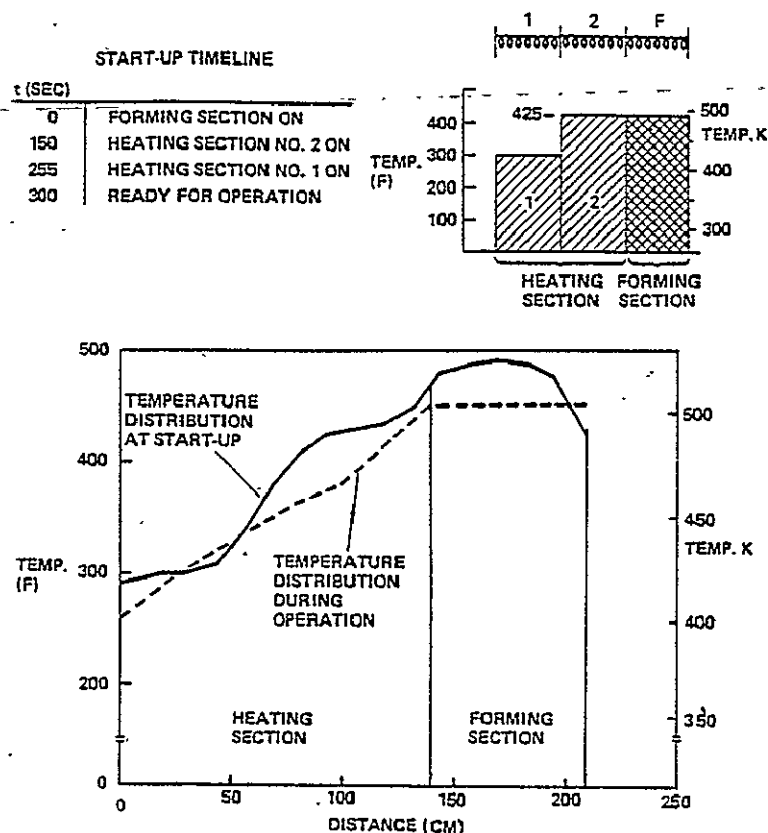


Figure 3-8. Start-up Timeline and Temperature Distribution

sensors of the same type as used in the heating section. Both heating and forming section heaters are shown as separately driven by an electrical source (shown here as 28 volts DC; TBD) through controlled switches, giving an on-off energizing mode as opposed to proportional-control mode. The respective switches are activated based on data provided by the temperature sensors to the system processor, and on the active mode of the operation.

Following the heating and forming sections, the GTP material is cooled by cooling platens; these platens are shown as being controlled by actuators which are activated via a controlled switch closure to the 28 volts DC source.

Next in sequence is shown the drive motor which pulls the

GTP material through the system. This motor is driven via the application of excitation through a controlled switch closure. A travel sensor provides data to the processor as to the length of material which has been processed through the system prior to cutoff of the desired net length structure.

Two weld heads join the cap section to two respective cross members and related diagonal stringers. Bi-directional motors transfer the weld heads up to and away from the material area upon command of the processor. Final positioning of the weld heads prior to activation is based upon data to the processor, provided via weld head position transducers. Weld application is controlled by the processor via control of the weld supply.

The last operational phase of the system is the shearing-off of the individual caps of the completed system. The shears are shown as actuated through switch closure to the 28 volts DC source.

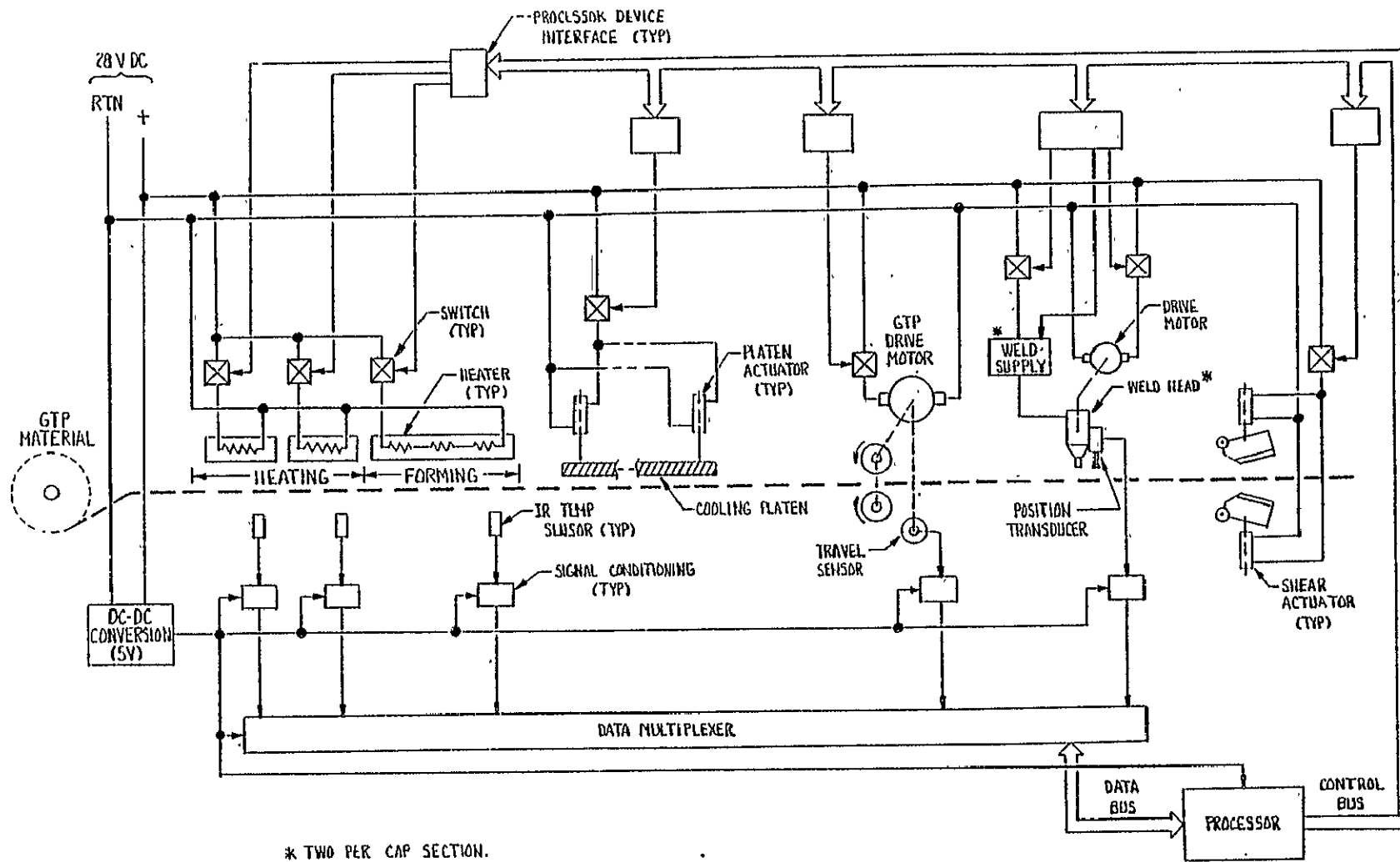


Figure 3-9. System Functional Control Diagram

A 5 volts DC-to-DC converter is shown as representative of the voltage conversions necessary to energize signal conditioning for the various sensors, the data multiplexer, and the processor. The data multiplexer provides the signal conditioning outputs, in suitable form, to the processor via a data bus. The data bus is shown as bi-directional, indicating the control the processor has over data flow. The processor control bus interfaces each of the functional areas via device-peculiar interfaces, each compatible with the individual device requirements. Not indicated in the diagram is a processor interface to the Shuttle operator area. This interface will allow operator monitor of the process, and operator update of desired operational activity of the system.

3.1.5 EVALUATION AND SELECTION. The rolltrusion process is a straightforward forming method usable with heat-softening materials. The alternative processing steps have been described and evaluated elsewhere in this report. These are summarized in Table 3-1. In assembling major assemblies to form a beam fabrication machine the following criteria have been applied to achieving a soundly integrated system design, and carried over to the ground machine.

1. Maximize electrical/thermal conversion efficiency
2. Modularize for downstream adaptability
3. Assure mission sharing on Orbiter flights
4. Minimize new development to constrain costs

Within the load-carrying capability of the shuttle orbiter weight of the experiment payload was not critical. Standard aerospace lightweight approaches were used throughout and overall weight minimized. Assurance of mission sharing was achieved by limiting cargo bay volume usage to less than one half of the available space. Machine potential reliability was enhanced by keeping complexity to a minimum. Where operating functions have a fixed relationship they are mechanically linked whenever possible with redundant controlled drive points. Design fixes for hypothetical problems have been considered and, pending hardware tests showing a need, installation provisions have not been inhibited.

The machine's basic structure comprises a strongback around which the machine elements are attached as separately assemblable and testable modules. For ground maintenance purposes all elements are easily accessible. On-orbit maintenance for the experimental version is not a groundruled requirement.

Every effort has been made to keep down the costs of developing and performing the experiment mission within prescribed groundrules. The approach to cross member fabrication is a case in point. The selected machine approach is to form each cross member from GTP strip using the same technology developed for the cap sections.

Table 3-1. Machine Functional Design Selections

Function	Alternatives	Selection	Rationale
1. Material Storage	a. Wound on reel with drag brake and enclosed in can b. Roll in a can running on outside rollers. Inter-laminar drag.	a.	Controllable drag load. Ease of reloading.
2. Heating	a. RF b. Microwave c. Induction d. Resistance e. Ultrasonic	d.	Highest electrical/ thermal conversion efficiency. Lowest relative cost. Highest reliability.
3. Forming	a. Rollers b. Fixed guideways c. Matched forming tools	a.	Best control of shape. Redress of abnormali- ties.
4. Cooling	a. Conduction to cold plate b. Radiation to cold wall or space	a.	Higher performance Higher final form accuracy
5. Driving	a. Cylindrical drive rollers on flats of section b. Spherical drive rollers on flange radii of section	a.	No scuffing. Drive force at centroid.

The members are sheared to length and mechanically placed in position for welding. An alternative approach is to manufacture the cross members on the ground and dispense them from magazines attached to the machine. This method reduces electrical heating requirements by twenty per cent. It also introduces a new development item with associated increased costs. Since satisfactory machine performance is available well within the Orbiter power supply capability, the power usage reduction benefits was judged not worth the increase in development cost.

In the next subsection the procedures for orbital deployment, testing, and beam retrieval are established. The driving criteria are development of data on the performance of the beam fabrication machine. Both dynamic and thermal testing of the beam produced are proposed. After return of beam sections to the ground physical inspection and structural testing will be performed to complete the data gathering.

The recommended beam fabricator arrangement and design approach comprises six rolltrusion heads equally spaced around a hexagonal strongback. Three heads produce continuous cap sections ; three heads produce and cut to length individual cross members. Three swinging double arm cord dispensers lay down the diagonal bracing across the beam bays. Six ultrasonic weld heads trap and weld the cords between the cap and cross member attachment surfaces. Three shearing devices sever the cap sections when the desired beam length has been produced. Operational control of the machine is performed by a preprogrammed microprocessor unit with initiation and override controls placed at the Orbiter mission specialist station. Electrical/electronic control equipment units and power supplies are mounted accessibly to rolltruder module support structure. The modularity of major assemblies provides flexibility for rearrangement to accommodate specific application constraints in other uses.

There are potential problem areas which appear to require further study and/or breadboarding development in any next phase of this program. These are:

1. Heater element design for sturdiness, long life, and minimum thermal inertia.
2. Temperature sensing of the GTP strip for calibration accuracy and control sensitivity.
3. Variability of Orbiter power source voltage between 27 and 32 volts dc which may require experiment power conditioning/regulation to, say, 24 VDC.
4. Design of the cap section/cross member/diagonal cord welded joint to meet structural requirements.

3.2 OPERATIONAL PROCEDURES

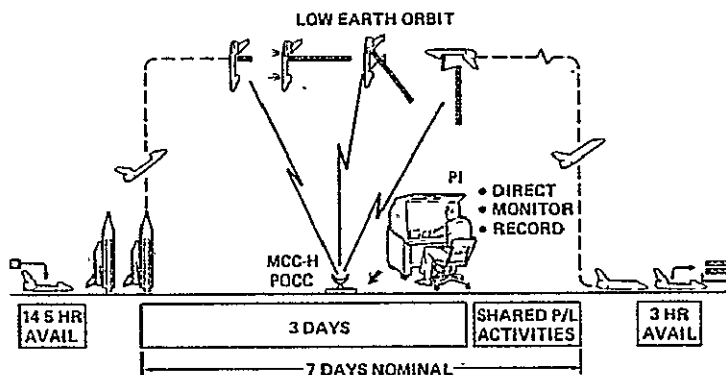
The groundrules and assumptions for the flight experiment are given in Section 1. Figure 3-10 shows the proposed mission profile for the LSSFE mission.

During prelaunch operations, the LSSFE payload is allocated up to 14.5 hours as part of the Orbiter processing flow to complete payload installation, interface verification and testing with the Orbiter.

During ascent to or return from the delivery orbit, the LSSFE equipment is inactive - requiring only mechanical and caution and warning support from the Orbiter. The nominal mission duration is 7 days, however, the LSSFE is expected to need about 3 days - with the remaining period available for co-passenger payload activities. During the experimental beam building operation, the equipment operates automatically under control of the experiment computer. The Orbiter crew initiates each operational or test phase and controls Orbiter maneuvers and RMS operations. An experimental beam of up to 100 m length will be fabricated for on-orbit verification of beam fabricator operations and for test. Test instrumentation is added to the beam using EVA.

Housekeeping and test data will be stored on payload provided recorders in the bay and also monitored at the aft flight deck payload station. Data will be transmitted to the ground where it will be displayed and recorded.

At the conclusion of the testing period the beam will be cut into about twelve lengths using the RMS to grapple the structure and EVA/hand tools to sever cap sections and cords. The beam sections will be stowed around the first nine meters of beam protruding from the machine for return to earth. This will be done prior to beginning preparations for descent (experiment termination, securing, Orbiter thermal conditioning, etc.). After landing, up to 3 hours is allocated for payload removal.



Executive control and monitor of the beam fabrication on-orbit operation is provided via the Orbiter RF command link ground controllers at the Payload Operations Control Center (POCC) which is co-located with Mission Control Center - Houston (MCC-H). MCC-H provides Orbiter and overall mission control.

Figure 3-10. LSSFE Mission Profile

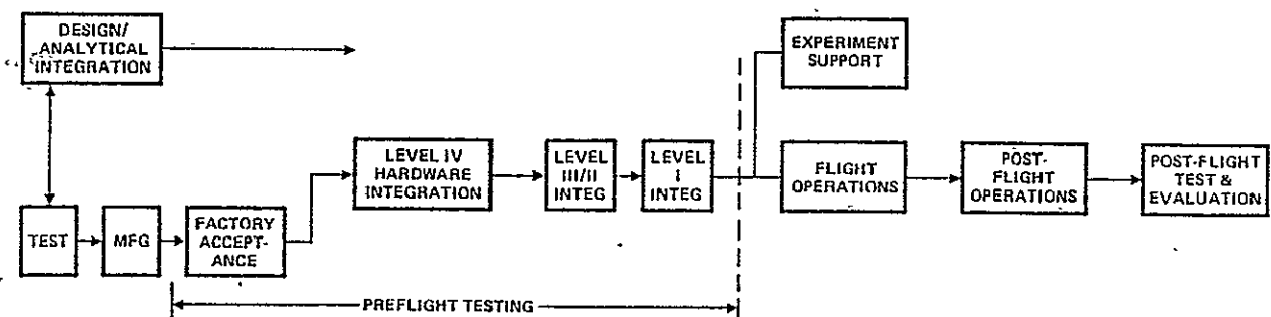
3.2.1 GROUND OPERATIONS. Ground operations for LSSFE comprise three major activities, namely, acceptance testing, equipment integration, and launch site operations.

Figure 3-11 depicts LSSFE program activities during the development and operations phase. Ground operations related to preflight testing for the flight article are summarized according to task. The level IV integration is assumed to be at MSFC, the remainder at KSC.

Factory acceptance testing will include a test in which a short length of beam will be fabricated and cut off. A beam length about one bay (or more) beyond the cutoff plane should be adequate. This test demonstrates the beam fabricator end-to-end functional suitability for flight and also "primes" the machine for on-orbit operations. A vacuum chamber is required for this test, minimum dimensions 8.5 m long by 3 m diameter. GSE requirements include power, heat rejection, and data acquisition/command. Mounting will be by the built in trunnion and saddle provisions.

After factory checkout the completed beam fabricator and support equipment will be delivered to MSFC for Level IV integration consisting of installation, interface verification, test and checkout activities which do not require a vacuum chamber. Typical tasks are: installation of experiment equipment on Spacelab pallets, beam fabricator alignment with pallet, electrical and data interface proofing, software checkout with Orbiter GPC simulation, and function tests. A preliminary Level IV integration flow diagram is shown in Figure 3-12. The corresponding requirements are summarized in Table 3-2.

• PROGRAM ACTIVITIES FLOW



• PREFLIGHT TESTING SUMMARY

FACTORY ACCEPTANCE TEST
LEVEL IV

LEVEL III/II

LEVEL I

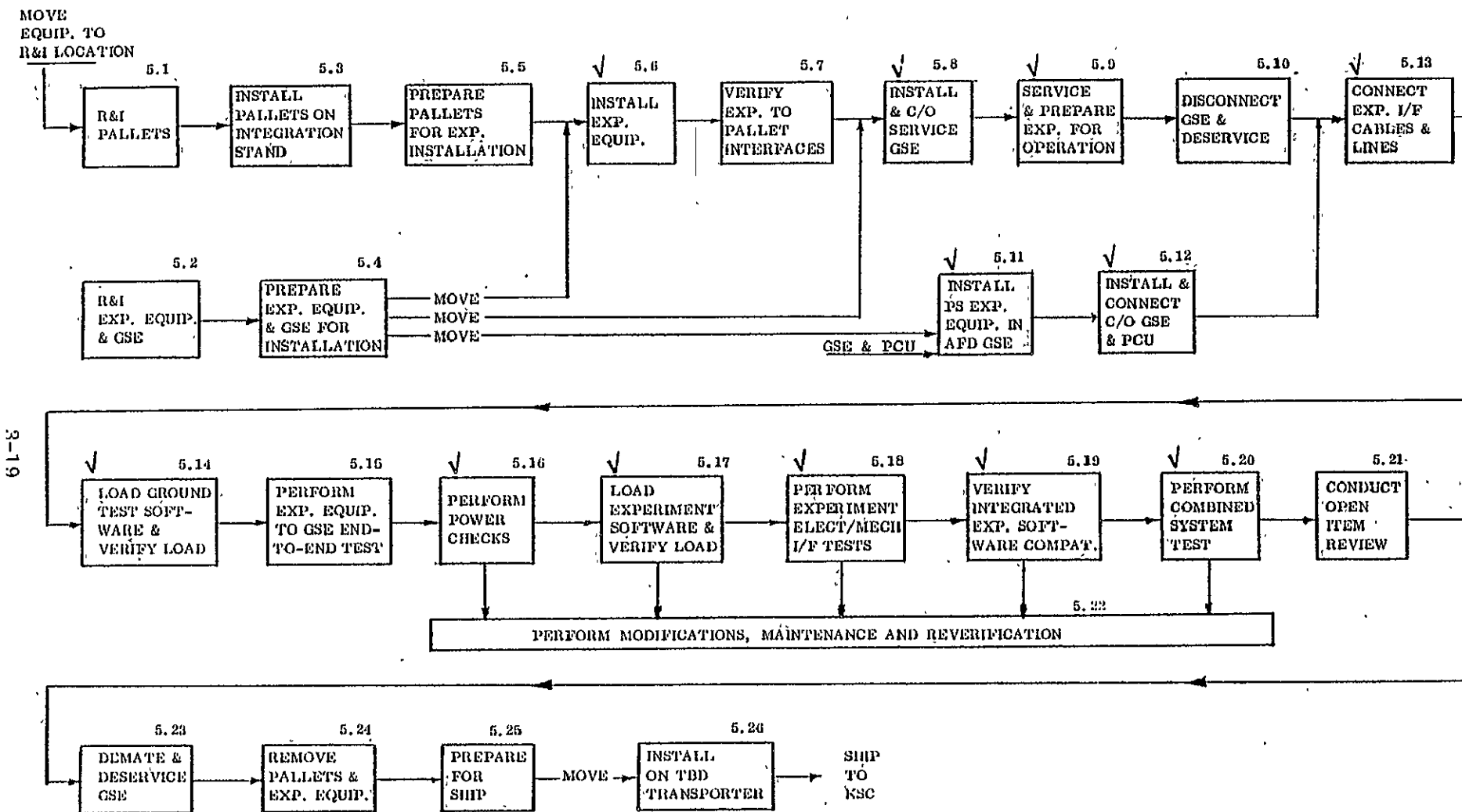
TASK

END-END FUNCTIONAL TEST AND PRIME SYSTEM
INTEGRATION AND CHECKOUT OF EXPERIMENT
EQUIPMENT WITH PALLETS

COMBINATION AND INTEGRATION OF COMBINED
EXP EQUIP AND PALLETS WITH FLIGHT SUPPORT
ELEMENTS

INTEGRATION AND CHECKOUT OF SPACELAB AND
PAYLOADS WITH SHUTTLE

Figure 3-11. LSSFE Development and Operations Phase Activities



* BASED ON SIMILARITY WITH OPT 6 - REF SPACELAB INTEG. STUDY, MSFC, FEB. 1977.

Figure 3-12. Preliminary Level IV Integration Flow Diagram*

Table 3-2. Level IV Integration Requirements Summary

<u>FUNCT NO.</u>	<u>FUNCTION</u>	<u>EXPERIMENT REQUIREMENT</u>
5.6	Install Exp. Equip	Install Beam Machine/Trunnion, Saddle Install and Align Return Beam Supports Install Instrumentation Control and I/F Panel Align Machine To Pallet Centerline Proof Install Shaker & Lines
5.8	Install & C/O Service GSE	Install & C/O (Freon Loop Servicer)
5.9	Service & Prep Exp. for Operation	Fill & Bleed Freon Loop Prep TV, Film Camera, Laser Load Tape Recorders & Film Cameras Load Dummy Return Beams Load EVA Equipment, Check Access
5.11	Install Exp. Equip in AFD GSE	Instrument Control, CRT, Keyboard, C&W
5.12	Install & Connect C/O GSE & PCU	Exp Signal/Control, Instrumentation
5.13	Connect Exp. I/F Cables & Lines	Megger, Continuity, Bonding, Grounding, Power Isolation
5.14	Load Ground Test Software & Verify Load	Simulation Software TBD
5.16	Perform Power-up Checks	Check Low Power Equip Cntl Circuits, Instrumentation, Laser, TV, Recorders
5.17	Load Experiment Software & Verify Load	Orbiter GPC Software FCU Control & Monitor Software
5.18	Perform Elect & Mech I/F Tests	Beam Fabricator Rotation & Lock (e.g., down lock, intermediate, uplock) Return Beam Support Pivot, Dummy Beam Clearance and Clamping T/V & Camera Syst Operation
5.19	Verify Integrated Exp. Software Compatibility	Experiment C/O, Control, Monitor (Orbiter GPC, FCU, GND Test Software)
5.20	Perform Combined Syst Test	Crew Command/Control Interfaces and Mission Sequence Simulation

Subsequent to Level IV, the flight unit will be delivered to KSC for off-line integration with the shared payload, simulation equipment, and with on-line Orbiter equipment. The LSSFE fabrication equipment will be installed with the Orbiter in the horizontal position in the Orbiter Processing Facility. The LSSFE equipment will not require special environmental monitoring or control during prelaunch ground operations nor time critical access at the pad. Equipment handling in the vertical position is not

planned; however, it is not precluded by the design. The requirements for Level III/II integration are given in Table 3-3 and for Level I in Table 3-4.

3.2.2 FLIGHT OPERATIONS. In order to synthesize and define a suitable mission for the LSSFE it is necessary first to establish the requirements for on-orbit testing i.e., in evaluation of the fabrication process, testing and evaluation of the deployed beam, and return of beam sections to the ground for detailed examination.

3.2.2.1 Test Requirements — Measurements and observations will be taken during the fabrication of the test beam to evaluate each of the operational functions of the beam fabrication machine, namely; storage, heating, forming, cooling, feeding, positioning, welding, and shearing. A nominal operational cycle is performed as follows:

The machine has a run period during which the caps and beams are advanced at 2.2 meters per minute during a 40 second run time.

Table 3-3. Level III/II Integration Requirements

<u>INTEGRATION OPERATIONS*</u>	<u>REQUIRED FOR</u>
• INSTALL SPACELAB PALLETS IN TEST STAND	SHARED PAYLOAD
• INSTALL EXPERIMENT EQUIPMENT IN AFD GSE	"
• INSTALL EXPERIMENT GSE	"
• CONNECT AND VERIFY GSE - TO - EXPERIMENT INTERFACES	"
• SERVICE AND PREPARE PAYLOAD FOR OPERATION	FLIGHT EXPERIMENT
<u>LOAD - SHAKER WITH PACKAGED ELECTRICAL & FREON LINES</u>	
PACKAGED SHAKER DRIVE ADAPTERS	
RECORDER TAPE REELS (DATA & VIDEO)	
CAMERA MAGAZINES	
PACKAGED LASER REFLECTORS WITH BRACKETS	
PACKAGED ACCELEROMETERS & TEMPERATURE SENSORS	
PORTABLE WELD UNIT	
<u>SERVICE - FILL AND BLEED FREON LOOP</u>	
• POWER UP TESTS	SHARED PAYLOAD
• LOAD EXPERIMENT FLIGHT SOFTWARE AND VERIFY LOAD	"
• PERFORM MISSION SEQUENCE SIMULATION	"
• RESERVICE EXPERIMENT EQUIPMENT FOR FLIGHT	FLIGHT EXPERIMENT
• REMOVE EQUIPMENT FROM TEST STAND AND GSE AND MOVE TO ORBITER PROCESSIVE FACILITY	
* CONDUCTED IN THE OPERATIONS AND CHECKOUT BUILDING	

Table 3-4. Level I Integration Requirements

- INSTALL SPACELAB PALLETS IN PAYLOAD BAY
- INSTALL EXPERIMENT EQUIPMENT AT AFD PAYLOAD STATION & ON-ORBIT STATION
- CONNECT AND VERIFY ORBITER TO PAYLOAD INTERFACES
 - POWER - STA X₀ 695, AFD AND AT PALLET I/F
 - SIGNAL/CONTROL - STA X₀ 576, AFD AND AT PALLET I/F
 - PAYLOAD HEAT EXCHANGER - SUPPLY/RETURN STA X₀ 636, AND AT PALLET I/F
 - RMS GRAPPLE DEVICE
- PREPARE FOR ORBITER INTEGRATED TESTS
 - LOAD EXP. FLIGHT SOFTWARE AND VERIFY LOAD
- PERFORM ORBITER INTEGRATED TESTS
- PAYLOAD FINAL SERVICING
 - CONNECT ORDNANCE (JETTISON DEVICES)
 - VERIFY LAUNCH LOCKS
 - REMOVE LENS COVERS FROM TV/CAMERAS
- STOW EQUIPMENT IN ORBITER CABIN

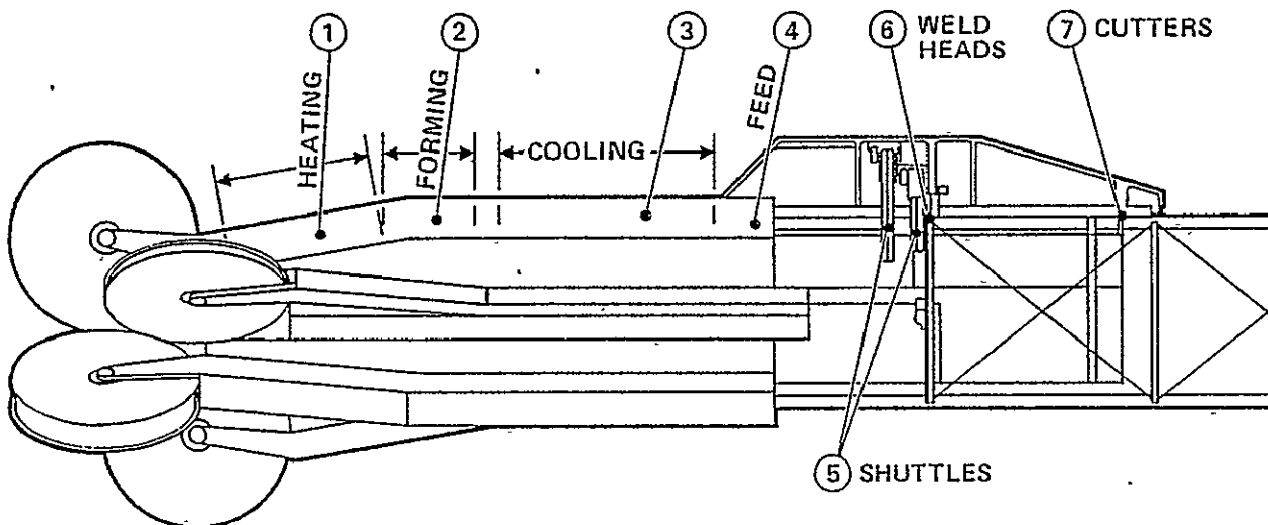
NOTE: TIME, ACCESS AND RESOURCES ARE ASSUMED TO BE SHARED WITH OTHER
ORBITER PAYLOAD ELEMENTS

After 1.434 meter beam extension, a pause of 40 seconds is made for cross-member and diagonal cord attachment. During the pause period the formed cross-members are grasped by the transfer mechanism, cutoff, and positioned on the caps. The diagonal cords are aligned between the cap and cross-member by the cord feed mechanisms and the cord and cap are ultrasonic weld joined to the cap. The machine then repeats the operating cycle.

Parameters such as temperature, pressure, flow rate, position, voltage and current will be measured and recorded for post flight analysis and for comparison with pre-flight test results. Important process control parameters will be displayed at the operating control panel and may also be displayed at the ground monitoring station.

Film and television cameras will be employed to observe and record the operation of feed, placement and clamping devices and to evaluate the operation of the cap and cross member cut-off shears. TV switching circuitry will be added to enable selective observation of the cameras on the CCTV monitors and transmission to the ground. Figure 3-13 shows typical camera locations and functions.

An electro-optical displacement measuring system will be employed to assess the geometric accuracy of the beam during and at the completion of the construction phase.

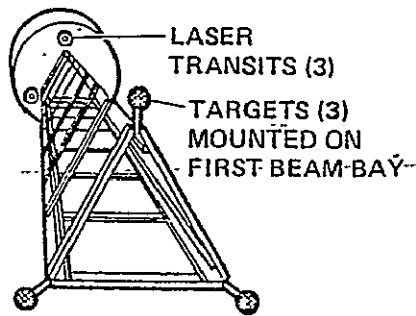


- | | |
|--|---|
| <p>① CAMERAS – OBSERVE HEATERS & REFLECTORS
TEMPERATURE – STRIP & REFLECTORS
VOLTAGE, POWER, ENERGY – HEATERS</p> <p>② CAMERAS – OBSERVE FORMING ROLLS</p> <p>③ CAMERAS – OBSERVE PLATEN SEGMENTS
TEMPERATURE – STRIP, PLATEN, COOLANT FLUID
FLOW – COOLANT FLUID</p> <p>④ CAMERAS – OBSERVE FEED ROLLERS
FORCE – FEED ROLLERS
ROTATION – FEED ROLLERS</p> | <p>⑤ CAMERAS – CORD PLACEMENT & TENSIONING</p> <p>⑥ CAMERAS – WELD HEAD & ANVIL OPERATION
– CROSS MEMBER PLACEMENT
FORCE – JOINT PRESSURE
TEMPERATURE – WELDS
CURRENT – WELD HEADS</p> <p>⑦ CAMERAS – CUTTER OPERATION
– SHEAR QUALITY (DEBRIS,
CRACKING)</p> |
|--|---|

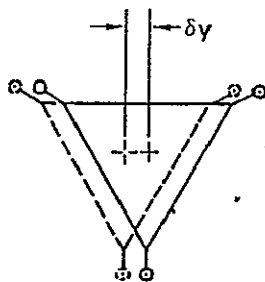
Figure 3-13. Typical Process Control Evaluation Measurements

The system will employ three laser transits which track the X-Y plane motion of optical targets mounted at the outboard end of the beam. The targets will be secured to the beam before flight using composite attachment brackets that are ultrasonically welded in place. The arrangement is illustrated in Figure 3-14.

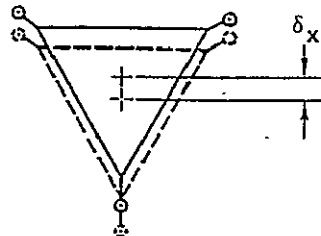
The output signals from the electro-optical trackers will be computer processed to evaluate bending and/or rotational distortion of the beam geometry. Since the beam structure will be excited by machine-induced forcing functions to oscillate at various natural frequencies as its length increases during the fabrication process, the tracker system must measure the peak-to-peak displacement and the direction of apparent motion of each of the three targets. The oscillatory motion must then be mathematically eliminated to determine the neutral position for each target. The computed neutral positions must then be compared to the location at which each target would reside if there were no bending or twisting deflection, and the static bending and/or twisting bias computed.



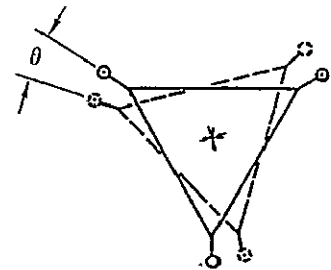
- OPTICAL DISPLACEMENT MEASURING SYSTEM UTILIZES THREE LASER TRANSITS WHICH TRACK MOVEMENT OF TARGETS IN THE X-Y PLANE
- COMPUTER PROCESSING OF OUTPUT SIGNALS IS REQUIRED TO SEPARATE TRANSLATION/ROTATION BIAS FROM OSCILLATORY DISPLACEMENTS, I.E., "AC NOISE" SUPERIMPOSED ON "DC SIGNAL"
- PROVIDES BOTH STATIC & DYNAMIC (FIRST MODE) DEFLECTION DATA



Y - AXIS BENDING



X - AXIS BENDING



ROTATION

TARGET TRANSLATION/ROTATION RESULTING FROM MISALIGNMENT

Figure 3-14. Geometric Displacement Measurement

Experimental beam tests are required to verify the analytical models for vibration and thermal response developed to permit advancement to full scale large space structures. On-orbit tests are needed to obtain valid responses because of ground testing limitations related to vibration response in air vs. vacuum, gravity vs. zero gravity beam supports, and reproduction of thermal stimuli/response data. A suitable ground test facility would be prohibitively expensive to accommodate a 100 m beam and provide vibration and thermal inputs under vacuum conditions.

Requirements for vibration tests are given in Figure 3-15. Tests will be performed using the 100 m long experimental beam, secured in the beam fabrication machine. Natural modes of vibration will be excited in bending and torsion. Beam responses will be measured to determine natural frequencies, mode shapes and structural damping factors.

Vibration forcing functions will be induced into the beam by alternately firing the Orbiter RCS thrusters to excite the lower frequency bending modes, and by employing an electrodynamic vibration exciter for the higher frequency bending modes and the torsional modes.

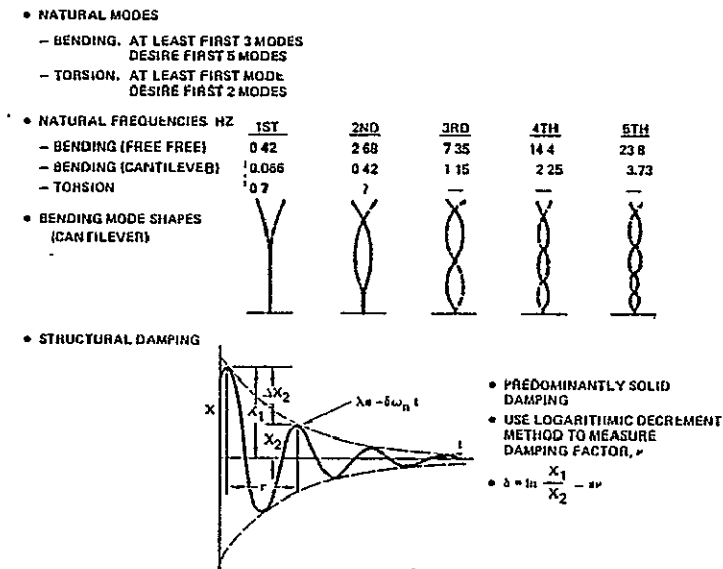


Figure 3-15. Vibration Test Requirements

function input location and the response measurement locations. Provisions should be made for vibration exciter inputs at several locations to insure non-coincidence with nodal points.

When using the RCS system for exciting the lower frequency bending modes, structural damping can be determined using the logarithmic decrement method. For the higher frequency modes, the vibration exciter force input measurement and beam response measurements can be digitally processed using Fast Fourier Transform techniques which yield natural frequencies, damping factors and mode shapes.

The lower frequency bending modes can be excited by alternately firing the Orbiter RCS thrusters to produce angular acceleration about the roll axis or translation acceleration along the Y-Axis. This is shown in Figure 3-16.

If roll excitation is employed, firing can be restricted to use only downward firing thrusters to avoid impingement of the exhaust gas plume. Slight orbital perturbations would result from downward-only firing. If translation excitation is employed, thruster plume impingement effects are avoided but a roll moment is created if only horizontal firing thrusters are fired. This can be neutralized by additionally pulsing downward firing thrusters on the opposite side.

Excitation by the RCS system is not expected to be useful for the torsional mode tests because they will have relatively high natural frequencies and because the beam neutral

The natural response frequencies will be dependent on the beam end condition. If the machine clamps the beam firmly and the machine, pallet and attach fittings act as rigid members the beam will respond as a cantilever configuration, with very low resonant frequencies. However, if the clamps, machine structure, pallet structure and attach fittings provide compliance in mounting, the beam response could approach the free-free configuration. The actual case will probably lie between these extremes.

The bending mode shapes for the higher frequency modes will influence the forming

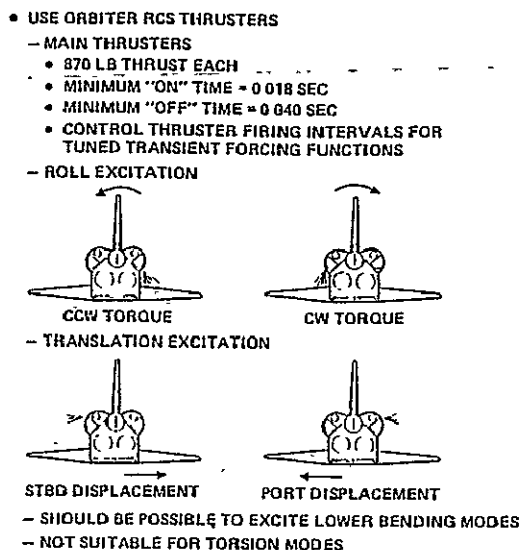


Figure 3-16. Vibration Excitation Options

Ideally, the forcing function waveform should be a pure sinusoid, tuned to each of the individual beam resonant frequencies. However, the square wave nature of the thruster-produced force vs. time history will tend to excite the odd numbered higher harmonics and cause a complex response which obscures the desired response. Further study should be made of the possibility of constructing a "shaped" transient forcing function by selectively programming the on-off sequence of the individual thrusters. See Figure 3-17.

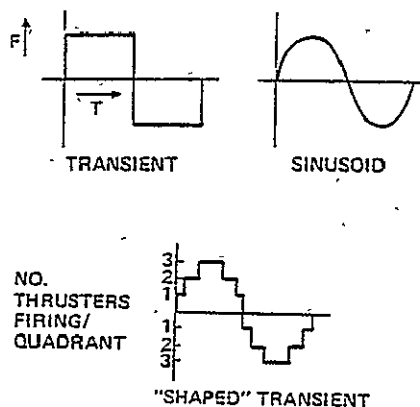


Figure 3-17. Forcing Function Wave Forms

axis cannot be conveniently located at the yaw axis.

Use of the Orbiter thrusters for exciting beam natural modes of vibration appears to be feasible for exciting the lower frequency bending modes, but additional investigations need to be made into several areas.

Generating an oscillatory motion using the thrusters requires that a control signal be introduced into the Orbiter's GN&C subsystem. This will require that a feedback signal representing the beam's amplitude and phase response be measured, computer processed, and introduced at an appropriate place in the control loop. Analyses of the RCS subsystem must be performed to verify that the proposed mode of operation will not degrade the thrusters nor the structural mountings, plumbing, and associated components.

Beam natural modes of vibration, bending and torsional, can also be induced by incorporating electrohydraulic exciters in the mounting trunnion assembly. This method adds to the weight, complexity, and cost of the basic installation. It also requires the beam fabrication machine to transmit the vibratory force to the experimental beam, thereby adding new design loads and possibly impairing machine reliability.

Another available method is use of an electrodynamic vibration exciter unit with lightweight armature and large stroke capability.

One of the Orbiter RMS manipulators will be employed to position the electrodynamic shaker at several beam locations within the area accessible to the manipulator and within the operator's field of view, Figure 3-18.

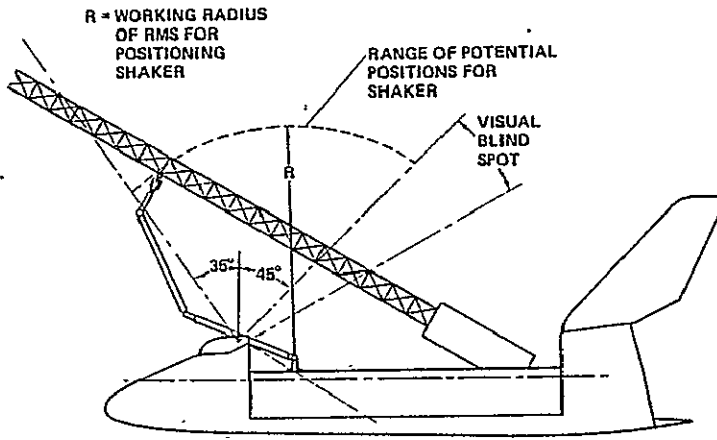


Figure 3-18. RMS Positioning of Shaker

The shaker will be a low force (50-150 lbf), long stroke unit, driven by a DC-coupler amplifier. The vibratory force input to the beam will be measured using a mechanical impedance head. The force and acceleration signals will be fed back to a digital processor for system control and modal analysis.

A high compliance suspension system will be used to mount the shaker to the RMS end effector, such that the shaker

acts as an inertial mass freely suspended in space. Prefabricated drive adaptors will be installed at several locations and orientations during the beam construction process by an EVA crewman. The adaptors will be stiff, lightweight assemblies constructed of composite material that will be ultrasonically welded to the beam cross members. Mechanical drive couplings will be employed that can be quickly engaged and disengaged by an EVA crewman.

Installation and relocation of the exciter at several beam stations and orientations will require the use of two RMS manipulators in a non-simultaneous operational mode, one for shaker positioning and one for EVA crewman mobility.

The factors which will influence the vibration test configuration are the type and input location of forcing function, accessibility by the RMS and EVA crewman, and visibility from the Orbiter aft flight deck, as illustrated in Figure 3-19.

For those bending modes excited by using the RCS thrusters the beam fabrication machine will be rotated upward, aligned along the Orbiter Z-Axis. Operation of the thrusters to produce roll or translation displacement will produce oscillatory beam response in the Y-Z plane, referenced to the Orbiter. Response monitoring accelerometers are mounted at eleven stations along the beam during the beam fabrication process; therefore, RMS accessibility to the beam is not required for this phase of the testing.

For the bending and torsional modes excited using an electrodynamic vibration exciter, the beam fabrication machine will be rotated downward to approximately

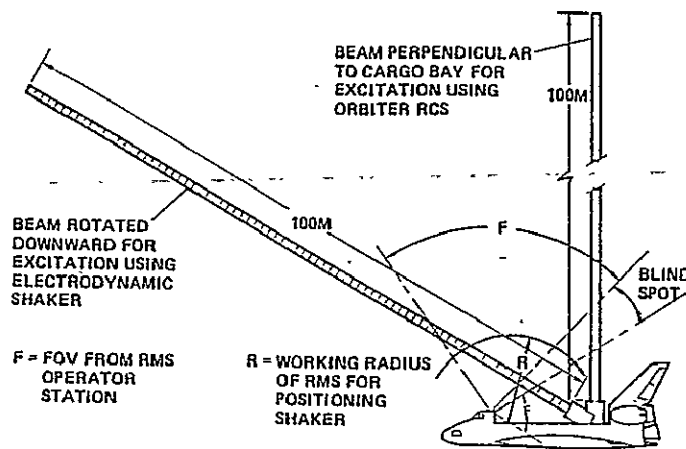


Figure 3-19. Dynamic Modal Survey Configurations

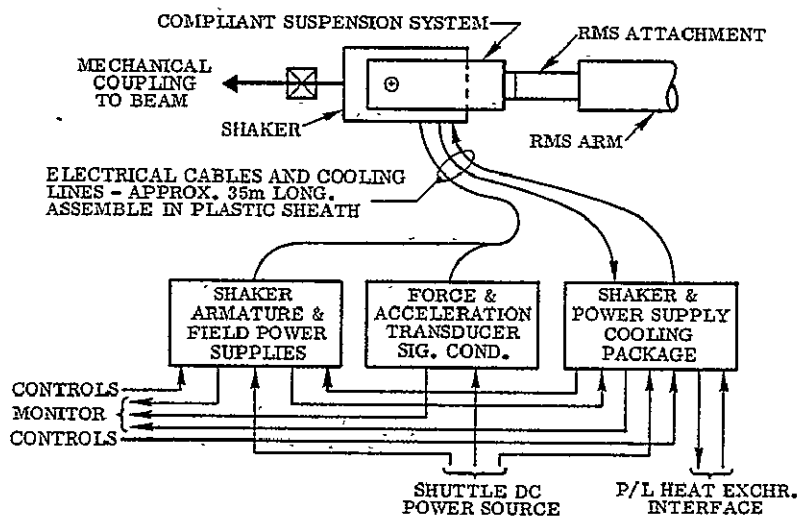


Figure 3-20. Shaker System Interfaces

cameras mounted on the pallet provide metric data for post flight analysis (low frequency modes only).

Inertial measurements use accelerometers installed at multiple stations along the experimental beam to provide response data needed to obtain the transfer functions. Many stations are desirable in order to provide sufficient amplitude and phase data for good resolution of the higher modes. However, installation of accelerometers and cabling requires EVA astronaut activity to unreel cables, position and secure transducers and tie down cables, during the beam fabrication process. A large number

30 degrees above the X-Y plane. At this angle, the RMS can reach to about the 12th bay of the test beam, and field of view (FOV) from the RMS operator station covers from the 6th to the 16th bays.

The shaker system interfaces with the experiment equipment and the Orbiter are shown in Figure 3-20.

Modal survey measurements are both optical and inertial. Optical measurements use laser transits mounted on beam fabricator which provide output signals (digitized) which indicate X-Y coordinates of laser targets. Real time data processing is required to separate bending and torsional misalignment (bias) from oscillatory responses. Accurate preflight alignment of the lasers and EVA installation of targets is required. TV cameras mounted on the beam fabricator provide a visual reference to crewmen controlling vibration inputs by display on monitors at the on-orbit station. The data is also recorded on a video recorder. Film

of transducers and associated cabling would mass load the beam and add damping, thus influencing modal responses. Fast Fourier transform (FFT) technique will enable using a limited number of accelerometers to obtain the data necessary to employ curve fitting algorithms for modal analysis.

Accelerometer assemblies are installed at 10 m intervals at 11 stations along the test beam. Two assemblies are installed at each station at two of the three corners. Bending and torsional vibration response components are resolved by the vibration analysis hardware and software. The vibration measurement instrumentation system installed on the beam must be designed for minimum mass and damping, and for ease of installation by EVA astronaut. Frequency range of interest is approximately 0.06 Hz to 30 Hz. Additional vibration measurements will be taken on the beam fabricator structure and on the pallet.

Beam-mounted instrumentation is pre-connected and stored in a protective container on the pallet. There are 22 accelerometer assemblies (44 channels) and 4 temperature sensors (8 channels). Additional accelerometers are installed on the beam fabricator structure and on the pallet during preflight operations. Other dynamic measurements to be made are vibration exciter force and acceleration inputs to the beam at the drive point. Total measurement channels proposed are:

Acceleration:	59
Temperature:	8
Force:	1

An accelerometer assembly installation is shown in Figure 3-21. The assembly contains two sensing elements with signal conditioning and multiplexer electronics. Assemblies are spotwelded to cross members by an EVA astronaut during beam fabrication. Twenty-two assemblies are required. Operational characteristics:

Frequency Range:	0 - 50 Hz
Acceleration Range:	-10 to +10 g
Temperature Compensation:	$\pm 2\%$ 172 to 338K
Internal A/D Conversion	

Thermal response tests will be conducted to verify analytical predictions of beam element temperature stabilization under various lighting and shadowing conditions. The proposed configuration is shown in Figure 3-22.

During mission Day 2, temperature measurements will be taken as the Orbiter passes from the earth's shadow into full sunlight and again 2 orbits later when it passes from sunlight into shadow. In addition to temperature vs. time recordings for each location, data describing Shuttle orientation and sun and earth viewing angles will be obtained to support post flight data analysis.

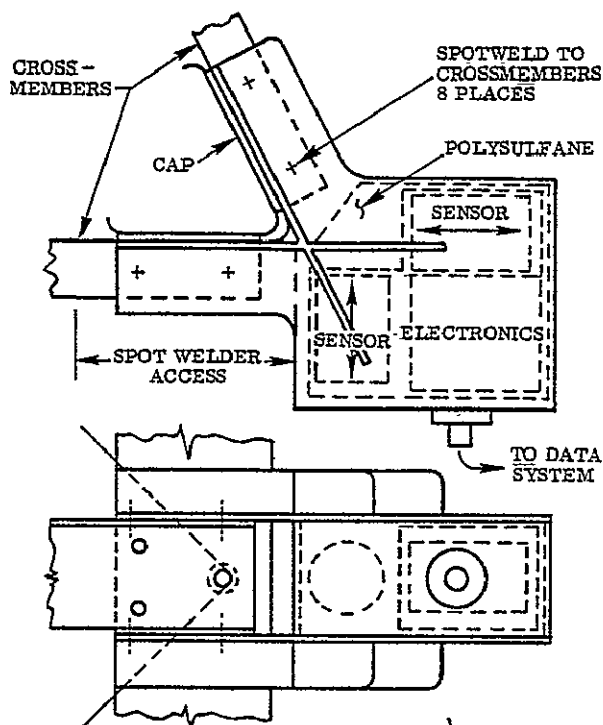


Figure 3-21. Accelerometer Assembly Installation

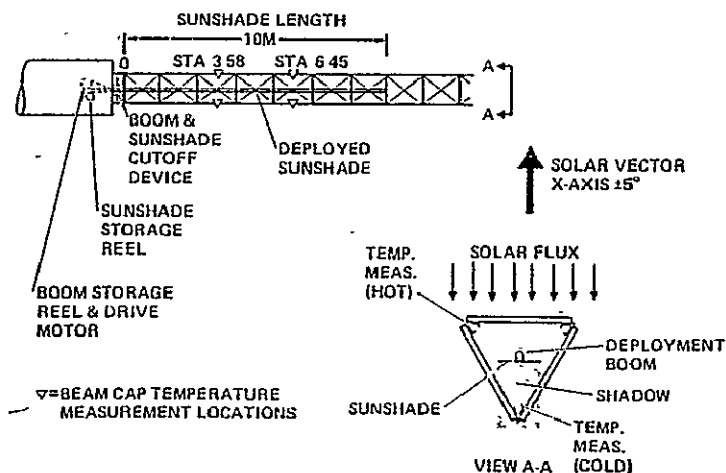


Figure 3-22. Thermal Test Configuration

During mission Day 3, tests will be conducted to determine worst case cap-to-cap Δt conditions. A ten meter long section of one of the beam caps will be artificially shadowed using a deployable sunshade perpendicular to the solar vector, thus producing a maximum heating condition on two of the caps. The third cap, in the shadow created by the sunshade, will stabilize at a low temperature. Temperature vs. time measurements will be taken on the caps at the centers of the 3rd and 5th bays as the Orbiter passes into and then out of the earth's shadow.

During the thermal tests, the electro-optical displacement measuring system will be employed to detect thermally induced distortions, if measurable.

Temperature measurements will be taken at four beam cap locations. However, due to the very low thermal conductivity in the transverse direction of the glass/graphite laminate, a single measurement would not be representative of the cap temperature for non-uniform cap insolation conditions. For example, the two caps facing the sun in Figure 3-23 would each have one hot leg and one cool leg, due to self shadowing.

To obtain the required temperature data, dual temperature measurement transducers will be employed at each location that measure the temperature on both legs of the cap.

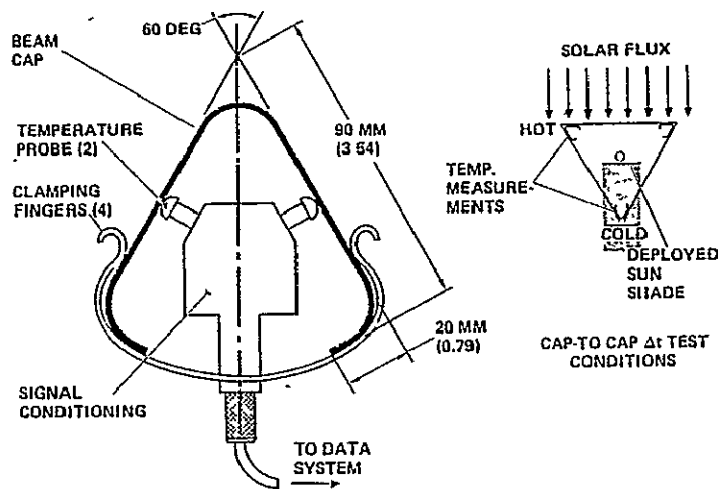


Figure 3-23. Beam Cap Temperature Measurements

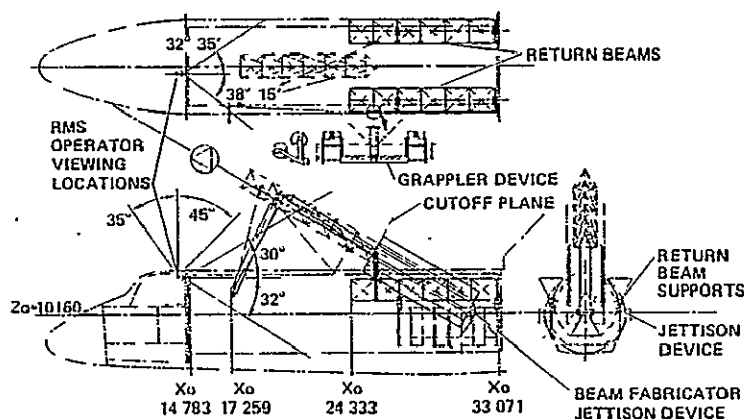


Figure 3-24. Return Beam Handling and Storage Concept

The temperature measurement transducers will be installed by an EVA crewman during the final phase of beam construction. The transducer will be designed to easily slip into place inside the cap and will be held in place with the desired contact pressure by integral spring clips. The transducers and their mounting provision must have no significant thermal effect on the cap response.

Implementation of a concept to handle and store beamed sections returned for post flight test and evaluation is shown in Figure 3-24. The payload provides supports for the returned beam sections and a special grapppler device with jaws which attach to a beam cap, straddling a cross member. The Orbiter provides the RMS to interface with the grapple device. The returned beam supports are located on the pallet sill and on the beam fabricator. Sill mounted supports pivot to provide clearance between fabricator rotation and the stored return beam. Mechanisms which extend beyond the Orbiter mold line during operation are equipped with pyrotechnic jettison devices. Nine of the eleven beam sections are clustered about and attached to the first nine meters of beam overhanging from the beam machine. All beam sections are severed to length

by an EVA astronaut and handled into stowage position by the remote manipulator system. During this process all critical locations, e.g., beam grapple point, storage locations, can remain in direct visual contact with the RMS operator at the On-Orbit Station.

Part of the fabrication flight experiment involves return of beam sections fabricated on-orbit for post flight test and evaluation. Typical ground evaluation tests of the returned specimen are identified in Figure 3-25. The returned samples must be of

• REQUIREMENT – FABRICATE BEAM ON ORBIT & RETURN TO EARTH
FOR POST-FLIGHT TEST EVALUATION

POST-FLIGHT TESTS	TEST OBJECTIVE	TYPE
CAP UNIFORMITY, DIMENSION	PROCESS QUALITY CONTROL EVAL START/STOP EFFECTS. POWER LOSS EFFECTS	NONDESTRUCTIVE TEST
CUT-OFF	MATERIAL SURFACE CONDITION	NONDESTRUCTIVE TEST
WELD	WELD STRENGTH, CONDITION	SPECIMEN CONSUMED IN TEST
BEAM DIMENSIONS	PROCESS QUALITY CONTROL EVAL (STANDARD BAY & SHORT BAY)	NONDESTRUCTIVE TEST
BEAM STRAIGHTNESS/TWIST, STIFFNESS	BEAM FABRICATOR PERFORMANCE	NONDESTRUCTIVE TEST
CRIPPLING LOADS	BEAM FABRICATOR PERFORMANCE	SPECIMEN CONSUMED IN TEST
GRAPPLE DEVICE INTERFACE	HANDLING EFFECTS	NONDESTRUCTIVE TEST

- DERIVED REQUIREMENTS/CONSTRAINTS – REPRESENTATIVE SAMPLES FOR PROCESS QUALITY
CONTROL EVALUATION
- RETURNED BEAM LENGTH COMPATIBLE WITH MISSION
SHARING AND ADEQUATE FOR GROUND TESTING

Figure 3-25. Return Beam Test and Evaluation

adequate length for the various tests and be representative samples of the on-orbit fabrication process. The return beam dimensions are further constrained by Orbiter bay length and with compatibility with potential shared payloads. Up/down payloads may differ; airborne support equipment for deployed payloads may remain in the payload bay throughout the flight.

Process quality control evaluation will benefit by having the total tested beam available for inspection. Two beams, each six bays long (~9m) are recommended for the major tests.

3.2.2.2 Mission Synthesis — Experiment orbit criteria and constraints are summarized in Figure 3-26 for an assumed launch in mid FY 1982. Acceptable orbit inclinations range from 28 1/2 to 57 degrees. Higher inclinations are not available until after 1982, nor are they required. Acceptable orbit altitudes range from 296 km to about 500 km. Above this altitude a typical payload would require one or more Orbiter provided OMS kits - which reduces payload bay length available. The lower altitude (296 km) is a standard parking orbit for upper stage delivery flights and is shown at the lower limit of the 13 payloads surveyed in the 1982 payload traffic manifest. These payloads are considered to represent typical candidate payload orbits which might be shared with the Large Space Structures Fabrication Flight Experiment.

• LAUNCH DATE – MID FY 1982

CRITERIA	CONSTRAINTS
THERMAL TEST REQUIREMENT – LIGHT DARK CYCLES	LOW ALTITUDE EARTH ORBIT
DYNAMIC TEST REQUIREMENT – NATURAL ILLUMINATION DESIRED DURING TEST PERIODS FOR TV/CAMERA	LONGER PERIODS OF NATURAL ILLUMINATION AVAIL ABOVE ~50° INCLINATION. LAUNCH WINDOW CONSTRAINED.
COST – STANDARD SHUTTLE ORBIT – ETR STANDARD SHUTTLE ORBIT – WTR STANDARD SSUS/IUS DELIVERY ORBIT	28½° & 56° INCLINATION 90° & 104° INCL AVAIL AFTER 1982 28½° AT 296 km
POTENTIAL FOR MISSION SHARING – BASED ON TYPICAL ORBITS ASSIGNED FOR FY 1982 PAYLOADS IN TRAFFIC MANIFEST (13 PAYLOADS SURVEYED)	
LENGTH AVAILABLE TO PAYLOAD	OMS REQUIRED ABOVE ~500 km, REDUCES LENGTH AVAIL BY 2.9m

- ORBIT CHARACTERISTICS – ACCEPTABLE 28½° TO 57°, 296 km TO 500 km
- RECOMMENDED 28½° @ 296 km MEETS TEST REQUIREMENTS WITH STANDARD ORBIT AND GOOD POTENTIAL FOR MISSION SHARING

Figure 3-26. Experiment Orbit Characteristics

The on-orbit thermal test requires periods of light and darkness that are available from low altitude earth orbits. The dynamic test has no "hard" orbital requirements although additional natural lighting available from certain higher inclinations orbits could be beneficial for supporting TV/camera instrumentation (accelerometers are the primary instrumentation planned for the dynamic modal survey).

The recommended orbit of 296 Km at 28.5 degrees meets the test requirements and uses a baseline Shuttle orbit from ETR with standard trajectory, mission planning, etc., available to payloads without special user charges. The orbit will also maximize potential opportunities for sharing the Orbiter weight/length/capabilities available to payloads.

Characteristics of a representative fabrication flight experiment mission are shown in Figure 3-27. The mission was synthesized to provide orbit constraint data for timelining experiment operations and tests.

A nominal orbit from within the acceptable range was selected. The launch date is consistent with current program plans. During each orbit a light/dark cycle occurs. The time period in total darkness during which the Orbiter is occulted from the sun by the earth, appears adequate to acquire thermal distortion and temperature measurement data used to validate analytical models. A plot of the beta angle is shown for a

NOMINAL ORBIT	ALTITUDE 296 KM, CIRCULAR
	INCLINATION 28½ DEGREES
LAUNCH	DATE 31 MARCH 1982,
	@ 12 00 GREENWICH
EXPERIMENT DURATION	~3 DAYS
ORBIT PERIOD	~1.5 HOURS
ORBITER OCCULTATION FROM SUN	~0.6 HOUR/ORBIT
SUN INCIDENCE ANGLE (β)	

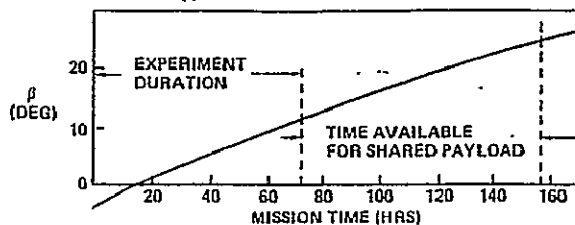


Figure 3-27. Representative Mission Characteristics

7 day mission (β is the angle measured between the earth-sunline and the orbit plane). The beta angle history of the representative mission precludes the need of any special Orbiter thermal conditioning maneuvers during the test period. At the end of the mission, up to a 12 hour period of thermal conditioning will be required prior to reentry. The mission timeline analysis indicates that a period of approximately 3 days will be needed for the on-orbit activation, checkout, fabrication and test operations. The remaining period is available for operations related to the shared payload. The sequencing of

co-passenger payload operations is not critical to the LSSFE payload. For example, an upper stage payload could be delivered before LSSFE operations begin.

The TDRSS will be operational and provides adequate communication contact coverage for ground monitoring and support based on the representative orbit characteristics and test orientations (X - Local Vertical, Z-POP or X - Local Vertical, Y - POP). TDRS contacts are sensitive to the orientation due to Orbiter blockage of the Ku - Band antenna. The addition of the optional Orbiter KuBand communications kit does not appear warranted. However, sizing of experiment recorders should consider communications gaps of up to about 20 minutes during critical test periods.

EVA appears well suited as a cost effective method to implement complex, non-repetitive experiment operations which involve installation of test instrumentation. An example is removing prepackaged accelerometers/temperature sensors with brackets and associated wiring from storage containers and welding them to the experimental beam during hold periods in the fabrication process. EVA can also be used to install laser reflectors and drive adapters and, with the support of the RMS, position/guide the attachment of the vibration exciter to the test beam.

Handholds will be required on the payload equipment to access the worksite (in addition to those already provided by the Spacelab pallet and along the Orbiter sill). A portable workstation such as described in JSC Report 10615 could be attached to the fabricator before launch and provide crew and tool restraints. Provisions for test equipment storage will be required, as well as a portable weld unit and its supporting resources (e.g., power). A major concern in the design of the payload systems and structures will be compatibility with the extra vehicular crewman's support equipment - particularly the life support systems and space suit components. EVA design criteria are documented in JSC-10615, May 1976.

Timeline analysis indicates that at least two one-man EVAs will be required for attaching test instrumentation. Less than half of the 24 EVA manhours available from the baseline Orbiter are needed for the planned fabrication flight experiment EVA operations. Figures 3-28, 3-29, 3-30 show preliminary timelines for typical experiment operations covering three days on orbit.

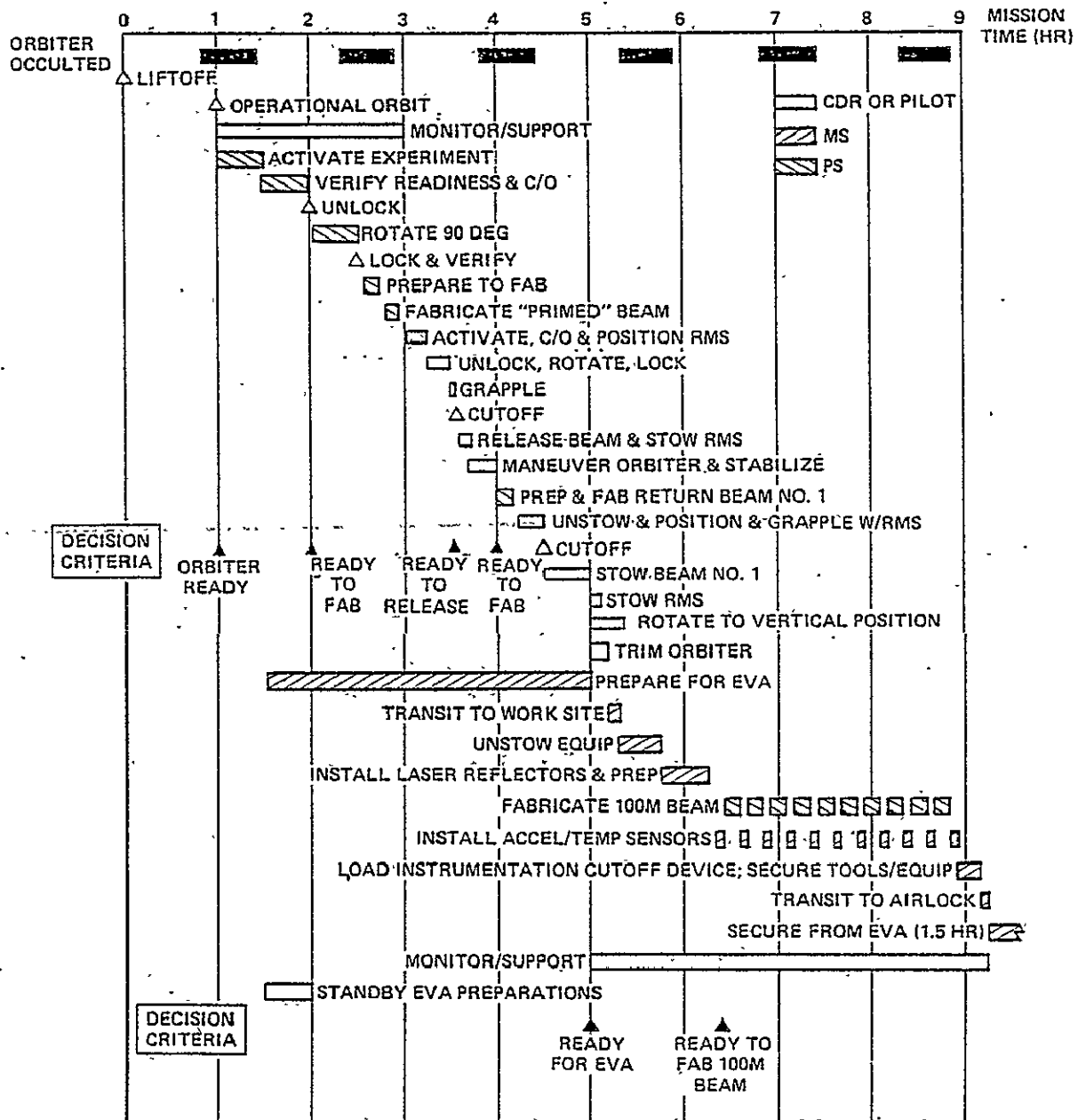


Figure 3-28. Mission Timeline — Day 1

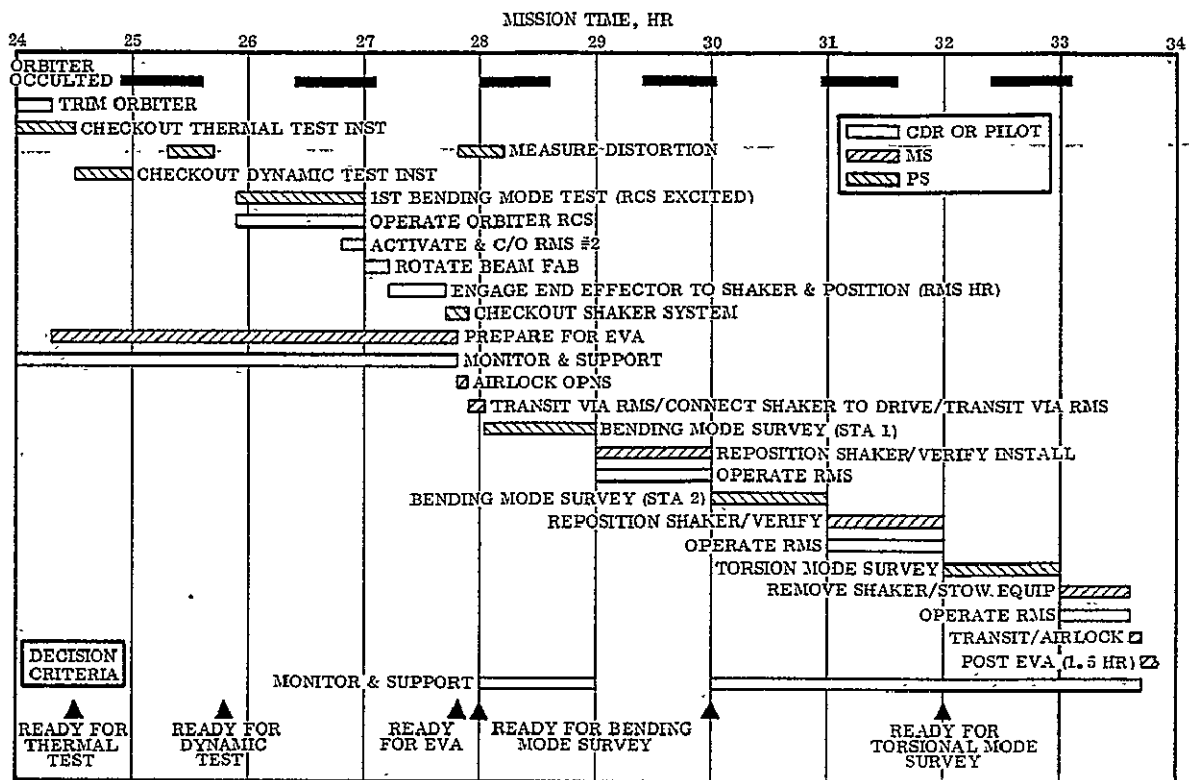


Figure 3-29. Mission Timeline — Day 2

3.2.3 STS INTERFACES. Figure 3-31 illustrates the experiment equipment installation and the major physical and functional interfaces between the pallet and the Orbiter. The beam fabricator is installed on a two segment pallet train using a trunnion attachment aft and a saddle attachment forward. The trunnion also provides for deploying the machine to a vertical position in the payload bay for fabricator operations or test.

The installed payload length is 9 m including overhang beyond the pallet and clearance for deployment. Locks are provided to secure the beam fabricator to the pallet during launch and landing. Standard Spacelab pallet segments provide structural mounting hardpoints for the beam fabricator. Other payload equipment may use inner skin mounting.

The power input cable, coolant supply and return lines, and the process control, TV, and test equipment/instrumentation cable harnesses mate with the pallet at an experiment provided interface panel to simplify Level I integration tasks. All experiment

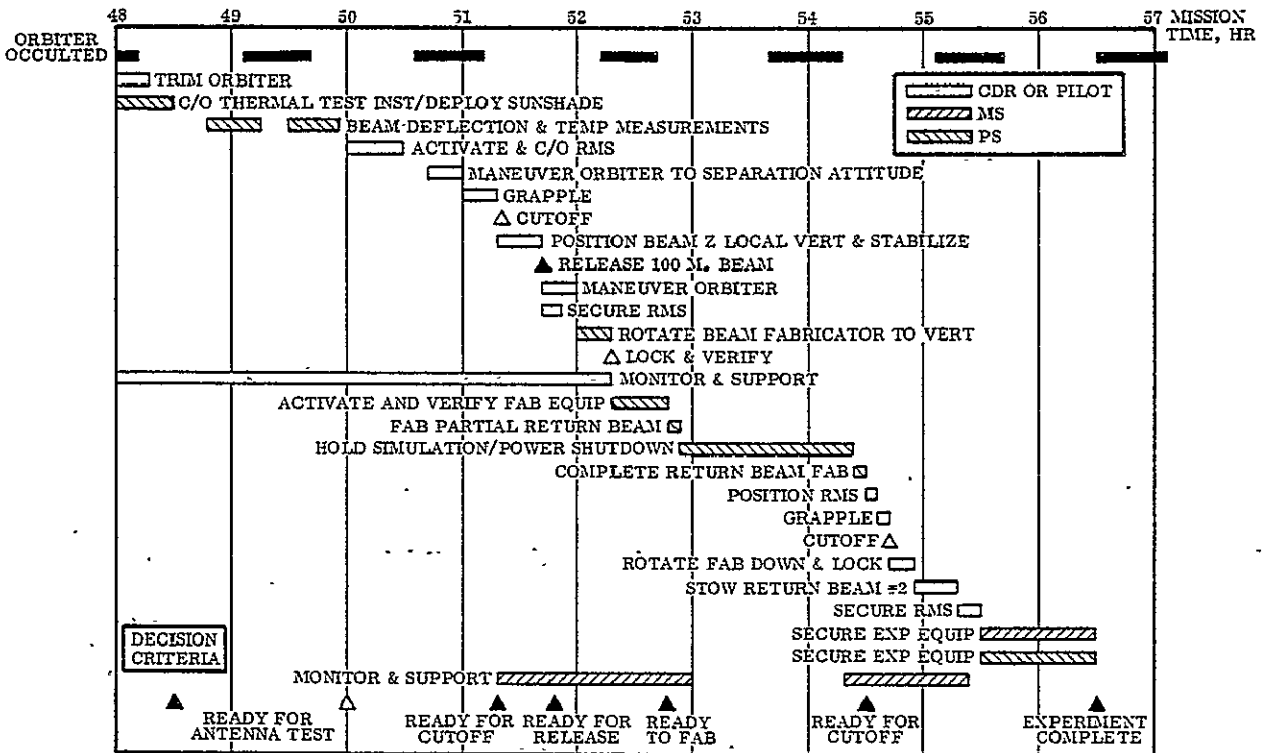


Figure 3-30. Mission Timeline — Day 3

equipment and interconnecting cables and fluid lines aboard the pallet will be installed and verified during prior integration activities.

Experiment equipment will be installed at the three work stations in the aft Flight Deck. Their locations are shown in Figure 3-32. The Payload Station will contain experiment equipment to operate and monitor the beam fabricator, test instrumentation, and vibration and thermal test equipment. The On-Orbit Station will house experiment equipment to control the erection of the fabricator by the trunnion assembly and to release and re-apply mechanical latches and rotational locks. Orbiter-provided equipment at the On-orbit Station will be used for Orbiter attitude adjustments, CCTV control and monitoring, external lighting control, and operation of the remote manipulator arms.

AFT FLIGHT DECK

CARGO BAY

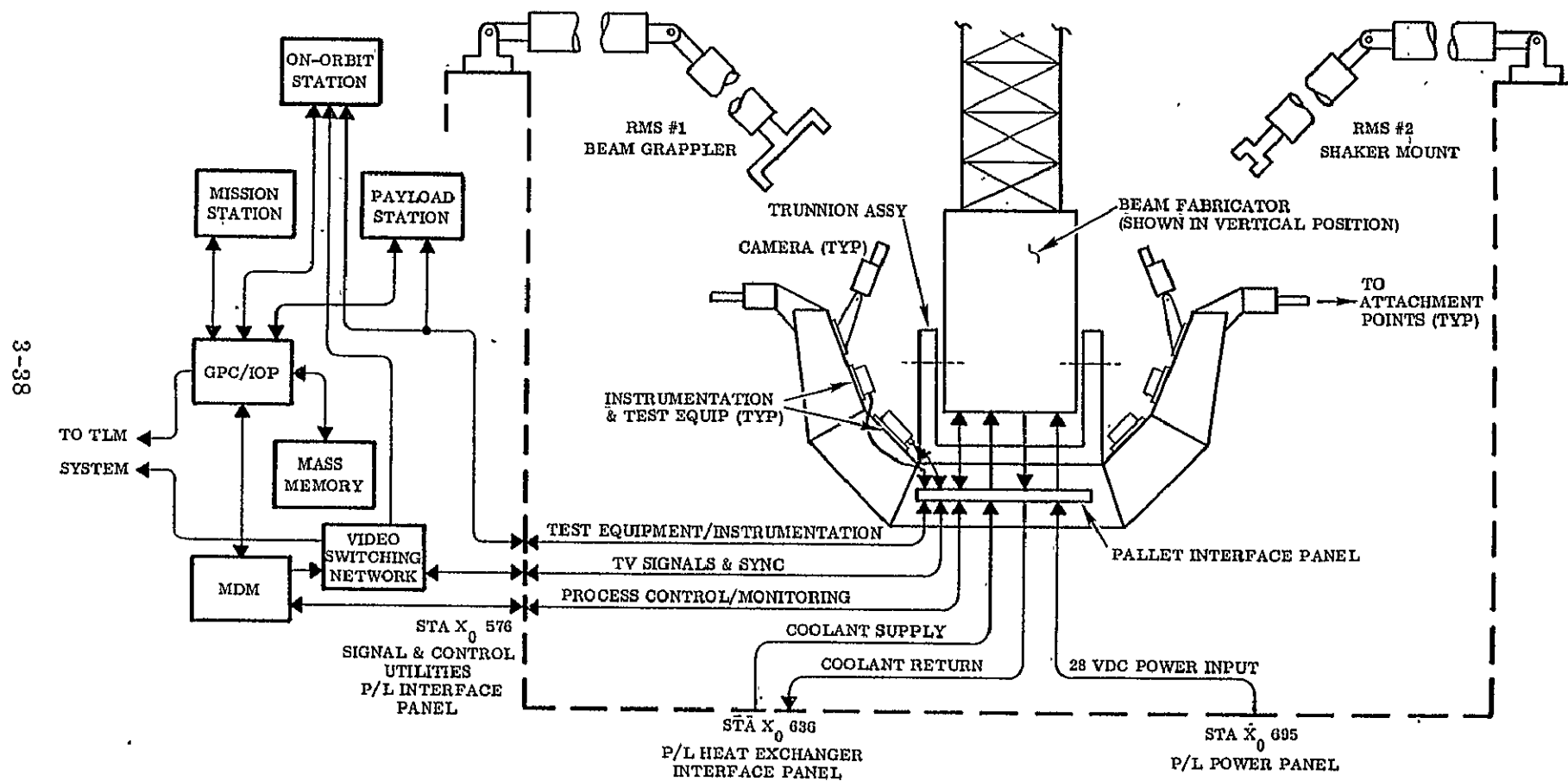
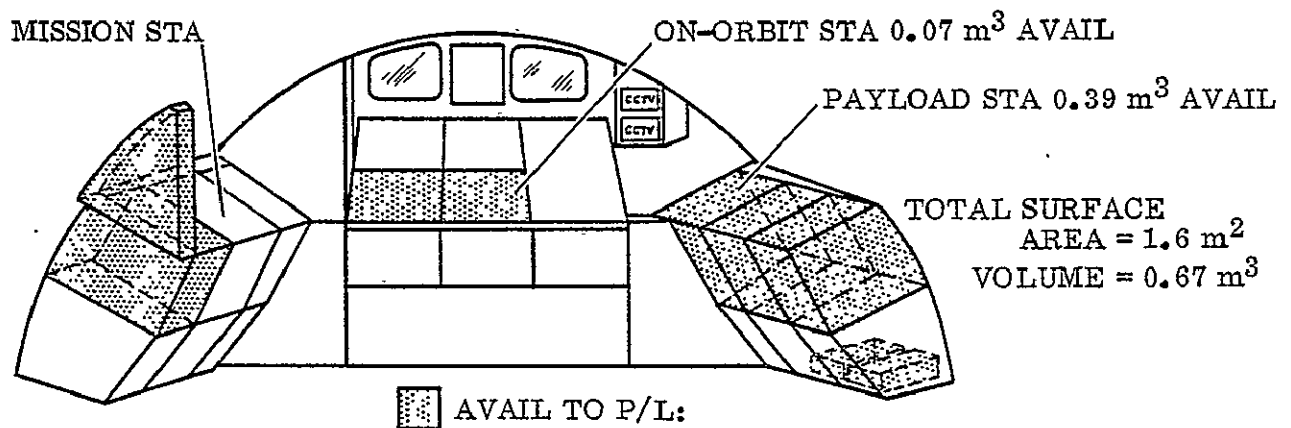


Figure 3-31. Experiment installation and Orbiter interfaces.



Mission Station	On-Orbit Station	Payload Station
Caution & warning displays	Fabricator erection controls Launch lock controls CCTV monitor switching CCTV camera controls	Fabricator operational controls & displays Fabricator evaluation test displays Vibration exciter system controls & displays Vibration analysis system controls & displays Sunshade operational controls Thermal test displays Instrumentation system controls

Figure 3-32. Payload Equipment Located at AFD

The Mission Station will contain an indicator light panel for caution and warning displays for flight safety critical functions such as launch locks. The Mission Station will also employ Orbiter provided equipment to control the transmission of test data and T.V. signals to the ground.

3.3 COST FACTOR EVALUATION

Experiment-related costs have been broadly assessed in two areas, namely, (a) a total flight experiment and (b) a ground demonstration fabrication machine. To accomplish (a) it was necessary to structure a preliminary development plan and this is presented also in this section.

3.3.1 PRELIMINARY DEVELOPMENT PLAN. This preliminary planning data provided top level development planning for Phase C/D of the Large Space Structures Fabrication Experiment (LSSFE) program. For preliminary planning purposes, the phases of the LSSFE program are:

LSSFE Study
(This Report)

- Thermoplastic Composite approach with following objectives:
 1. Conceptual design of a large space structures flight experiment.
 2. Preliminary design of a large space structures element fabrication machine for on-ground operation and proof of concept.

LSSFE Phase A

- Conceptual definition of flight experiment.
Completion of ground machine design.

LSSFE Phase B

- Flight Experiment Definition including predesign of composite fabrication machine (see schedule in Figure 3-33).

LSSFE Phase C/D

- Final design, construction, integration and operation for the on-orbit Fabrication Flight Experiment.

3.3.1.1 Program Definition for Cost Estimation — The program definition for cost estimation provides the data base for preparation of preliminary development plan and cost analysis data for the on-orbit fabrication flight experiment phase of the LSSFE program.

Ground Rules and Assumptions

The following Ground Rules and Assumptions have been made to scope the Phase C/D tasks:

1. The dimensions of the experimental beam to be fabricated on orbit will be assumed to be an equilateral cross-section approximately one meter high and 100 meters long.
2. The beam members will be formed of graphite/thermoplastic material.
3. Forming of members will use the "rolltrusion" technique developed by General Dynamics.
4. Fabrication processes developed for beam members will be applicable to all future large space structures to the greatest extent possible.
5. The machine concept developed for the flight experiment will be functionally identical and physically similar to the ground fabrication machine.
6. The on-orbit fabrication flight experiment will be assumed to be a payload on a Shuttle flight in 1982.
7. An interface with the Spacelab pallet will be assumed.

8. The experimentally fabricated beam will be returned to earth for examination and testing as part of the flight experiment.
9. On-orbit dynamic and thermal response tests will be performed as part of the flight experiment.
10. Interfaces with the Shuttle will be governed by the latest revision to JSC 07700, Volume XIV.
11. The Spacelab design concept to be used is the European Space Agency (ESA) Spacelab baseline as defined in the Spacelab Payload Accommodation Handbook, Review Issue, PDR-B 1976, with subsequent updates.

On-Orbit Fabrication Flight Experiment Mission Summary

The on-orbit fabrication flight experiment will be accomplished using one shared Shuttle flight. The equipment will be delivered and returned by the Shuttle from a low earth orbit. The experiment and its support equipment will be designed to use approximately one-half of the Orbiter payload bay. The experiment equipment will mount on a Spacelab pallet consisting of two standard 3-meter pallet segments joined to form a pallet train. On-orbit, an experimental beam of up to 100 m will be fabricated. The beam will be subjected to dynamic and thermal response tests while still attached to the Orbiter. The beam will be cut up and returned to Earth in sections for test and evaluation.

Tables 3-5 through 3-7 list the overall mission characteristics, the on-orbit flight experiment equipment, and equipment mass properties. The stowed and deployed orbiter installation and beam configuration requirements are shown in Figures 3-2 and 1-2.

Table 3-5. Mission Characteristics

<u>MISSION</u>	<u>CHARACTERISTIC</u>
Shared Shuttle Flight - % by length	50%
Duration (max.)	3 to 7 Days
Launch Date	3/1/82 - 6/1/82
Delivery Orbit (acceptable), Incl.	28½ to 57 Degrees
Delivery Orbit (acceptable), Alt.	296 to 550 Km, circ.

Mission Objectives

Fabricate Experimental Beam	100 m, max.
Install Evaluation Instrumentation	-
Perform Beam Response Tests, Dynamic/Thermal	-
Evaluate Beam Fabrication Stop/Start Cycle	-
Cut Beam into Sections	TBD Length
Return Beam Sections to Earth	-
Evaluate Returned Sections	-

Table 3-5. Mission Characteristics (continued)

ORBITER SUPPORT

Power	Baseline Orbiter -7kW
Thermal	Radiator Kit + Payload
RMS (1 provided in baseline)	2 Heat Exchange
Crew (Cmdr., Pilot, MS-1)	Baseline Orbiter
PS or MS-2	TBD
Airlock	Baseline Orbiter
Orbiter GPC	Baseline Orbiter
Orbiter Keyboard, CRT	" "
Orbiter MDM	" "
Structural Interface	" "
OMS Kit	Not Required
EVA (Portable Work Sta., Tools, etc.)	Required
Orb/Exp Umbilical (For Ground Power, Fluid, Data)	TBD

SPACELAB SUPPORT

Standard Pallet Structure (w/Hard Points)	2
Subsystem Igloo	Not Required*
Thermal Control (Cold Plate, etc.)	" "
Elect. Power Control/Distribution	" "
CDMS (Computer, EXP RAU, High Rate Multiplexer, Memory, Input/Output)	" "

Operations Support

Flight Operation	
TDRSS	X
POCC (Control/Monitor)	X
MCC-H (Std. Orb/Msn Control)	X
Ground Operations	
Launch/Landing Site	KSC
Level IV	MSFC
Off Line/On Line (Level III/II)	KSC
Post Mission (Equipment)	KSC/MSFC
Data Processing/Eval/Distribution	TBD

*An alternative experiment concept would use Spacelab pallet subsystems to provide resource support in lieu of direct Orbiter interfaces.

Table 3-6. On-Orbit Fabrication Flight Experiment Equipment/Support

ITEM	Quantity	
	Ground Development/Qual Test	Flight
Beam Fabricator	1 - E/A * 1 - Qual *	1
Beam Material (Thermoplastic Composite)	TBD	100 kg + TBD (Stored on Reels)
Test Instrumentation (Accelerometers, Laser Target, etc.)		TBD
Dynamic Excitation Equip (Pallet mounted)		TBD
P/L Provided Support		
<u>AFD Mounted</u> - Control & Display		TBD
<u>Bay Mounted</u> - Fabricator Trunnion Mount		1
- Beam Fabricator Saddle Support Struct.		1
- Beam Return Support Structure		2
- Interface Equip. to Orbiter, Pallet (Elect., Avionics, Mech, Fluid)		Cables & Lines Incl. in Exp. Equip.
Software	TBD	Orb GPC I/F Exp. Peculiar
Grapple Device (RMS Mounted)	TBD	1

* E/A = Engr. Article, Qual = Qualification

Table 3-7. Large Space Structures Fabrication Experiment
Preliminary Mass Properties - Shuttle Experiment Payload

SUMMARY

<u>ITEM</u>	<u>QTY</u>	<u>WEIGHT</u> (kg)
Beam Builder Support Structure	1	281.2
Cross Member Cutoff Mech	3	18.0
Cross Member Translation Mech	3	42.0
Bobbin & Traverse Mechanism	3	48.0
Ultra Sonic Weld Heads	6	30.0
Weld Head Positioning Mech	6	24.0
Cross Member Rolltruder Assy	3	417.3
Beam Cap Rolltruder	3	712.8
Beam Cut Off Mechanism	3	21.0
Electrical Equipment	-	236.0
Raw Material	100 m Beam +	120.0
Subtotal for Beam Builder		1950.3
Beam Builder Trunnion Mount	1	250.0
Beam Builder Saddle	1	100.0
Two Segment Pallet Train	1	1300.0
Return Beam Support Structure and Grapple Device	SET	35.0
Subtotal for Support Structure		1685.0
AFD Mounted Control & Display	SET	70.0
Instrumentation for Test	SET	1129.0
Experiment Support Equipment	SET	763.0
Optical Measurement/Observation Equipment	SET	225.0
Subtotal for Evaluation Test Equipment		2187.0
TOTAL PAYLOAD WEIGHT		5822.3

Ground Operations Scenario

After factory checkout the completed beam fabricator and support equipment will be delivered to MSFC (or other integration site) for Level IV integration consisting of installation, interface verification, test and checkout activities. Typical tasks are identified in Table 3-8. Prior to (or during) the Level IV integration flow, a short (length TBD) section of the experimental beam will be fabricated (this can only be done in a vacuum chamber) and cut off thereby demonstrating complete end-to-end functional suitability for flight. The flight unit is thus "primed" for on-orbit operation. Subsequent to Level IV, the flight unit will be delivered to KSC for off-line integration with shared payload, simulation equipment, and with on-line Orbiter equipment. The LSSFE fabrication equipment will be installed with the Orbiter in the horizontal position in the Orbiter Processing Facility. The LSSFE equipment will not require special environmental monitoring or control during any ground operations phase or time critical prelaunch access at the pad. Equipment handling in the vertical position is not planned, however, it is not precluded by the design.

Post mission operations will include equipment inspection, removal of the beam fabricator, support equipment and beam specimen(s) from the pallet. The location of post mission inspection/removal operations is assumed to be at KSC. The analysis of the returned beam(s) is assumed to be conducted by NASA/MSFC. Post mission analysis of the on-orbit test data including reduction, evaluation, and distribution is TBD.

Table 3-8. Typical Level IV Integration Tasks

Level	Integration Type*	Task	Reason
IV	I	Install equipment on Spacelab pallets	
IV	V	Electrical, data interface proofing	1st time all together (avoid later delays)
IV	T & C/O	Software C/O with Orbiter GPC simulation	"
IV	T & C/O	Align beam fabricator with pallet, funct. test	"
Pre-Level IV or Level IV	T & C/O	Produce beam segment	Prime fabricator systems and functional verification

* V = Verification, I = Installation, T & C/O = Test and Checkout

Categories of experiment peculiar GSE and unique facilities/special test equipment are identified in Tables 3-9 and 3-10, respectively. Equipment quantities are TBD. It is assumed that a GSE necessary to handle, transport, service, checkout and

maintain the Spacelab pallets is provided by the Spacelab program. Spacelab GSE will be available to support hardware installation and integration of the experimental flight equipment, and will provide simulations of any Spacelab interfaces which are required. Orbiter AFD interface simulation is assumed to be provided.

Table 3-9. GSE - Experiment Peculiar

Handling & Transport	
Dollies	x
Shipping Containers	x
Slings	x
Servicing	
Thermal Fluid (Freon)	x
C/O & Maintenance	
Integration - Software	x
- Elect/Funct. C/O	Various
Auxiliary Power Supply	x
Ground Heat Exchanger	x
Special (Auxiliary)	TBD
Sim. / Trainers	
Special EVA Tools	TBD
Exp. Peculiar RMS Tech. (Uses Avail JSC Simulator)	x
Mission Support	Provided
POCC * Console & Computer & MCC-H I/F Equip.	by POCC
POCC Software (e.g., Data Formatting)	"
Signal Format & Conversion Factors	Exp. Supp.
* POCC = Payload Operations Control Center	
x Required - Quantity TBD	

Table 3-10. Unique Facilities/Special Test Equipment

Design/Development - Fabrication	Clean Area (100,000 Class)
- Test	Vacuum Chamber
Integration	Clean Area (100,000 Class)
Prelaunch	
Mission Support	None
Post Mission	None

Mission Operations Scenario

During prelaunch operations, the LSSFE payload is allocated up to 14.5 hours as part of the Orbiter processing flow to complete payload installation, interface verification and testing with the Orbiter.

During ascent (or re-entry) to or from the delivery orbit, the LSSFE equipment is inactive - requiring only mechanical and caution and warning support from the Orbiter. The nominal mission duration is 7 days; however, the LSSFE is expected to need about 3 days - with the remaining period available for co-passenger payload activities. During the experimental beam building operation, the equipment operates automatically under control of the experiment computer. The Orbiter crew monitors the operation at the aft flight deck (AFD) and observes directly and with TV. The Orbiter crew initiates each operational or test phase and controls Orbiter maneuvers and RMS operations. Short beams will be fabricated, cut off and stored for earth return and evaluation. An experimental beam of up to 100 m length will be fabricated for on-orbit verification of beam fabricator operations and for test. Test instrumentation is added to the beam using an EVA work station.

Housekeeping and test data will be stored on P/L provided recorders in the bay and also monitored at the AFD payload station. Data will be transmitted to the ground where it will be displayed and recorded.

At the conclusion of the testing period the Orbiter RMS will grapple the beam and the beam will be severed by the beam fabricator cut-off device. The severed beam will be swung in close to the cargo bay and cut into sections using EVA and both RMSs. The sections will be stored in the cargo bay. The Orbiter will then begin preparations for descent (experiment termination, securing, Orbiter thermal conditioning, etc.). After landing, up to 3 hours is allocated for payload removal.

Executive control and monitor of the beam fabrication on-orbit operation is provided via the Orbiter RF command link ground controllers at the Payload Operations Control Center (POCC) which is co-located with Mission Control Center - Houston (MCC-H). MCC-H provides Orbiter and overall mission control.

Technology

Technology for the LSSFE program is considered to be within the state-of-the-art. Required technology for on-orbit fabrication techniques is identified in Table 3-11 and related to other program technology activities.

Table 3-11. LSSFE Technology

On-Orbit Fabrication Technique	Relation to Other Program Activities	Ranking
Beam Fabrication . Material Storage and Feed . Heating . Forming . Cooling . Driving . Welding . Shearing . Process Control	Functions demonstrated by ground machine	. Low . Medium . Low . Low . Low . Low . Low . Medium
Beam Joining	Demo in later flight tests	. Medium

3.3.1.2 Preliminary Development Plan

Schedule

A preliminary LSSFE program schedule is shown in Figure 3-33. Schedule and durations are based on the following guidelines and assumptions:

1. Phase B is required and produces the following products (as a minimum):
 - a. Requirements in the form of specifications.
 - b. Definition of the flight experiment.
 - c. A selected system predesign.
 - d. Plans and costs for development.
2. The design and analysis task and the ground test program will benefit from prior program activities. The ground test machine activities will be particularly important since the ground test machine is essentially a shuttle flight test prototype.
3. Analytical integration includes definition of the integrated payload system and compatibilities with the STS, mission and flight operations, verification, software integration, reliability and safety analyses, and configuration management. Analytical integration starts at the same time as design and analysis and concludes (for cost purposes) at the completion of the flight (sustaining support may be required until program completion).

4. Hardware integration span times are based on extrapolations of other Spacelab payloads.

Test Program

A preliminary estimate of LSSFE development and qualification testing for the on-orbit fabrication experiment is contained in Table 3-12. Key ground tests at the subsystem and system level are identified for development of mechanical and avionics equipment. A preliminary identification of component and subsystem qualification testing is included. It is assumed that one engineering article will be adequate for design support testing and one ship set will be used for qualification. Tests which require beam fabrication will be performed in a vacuum chamber.

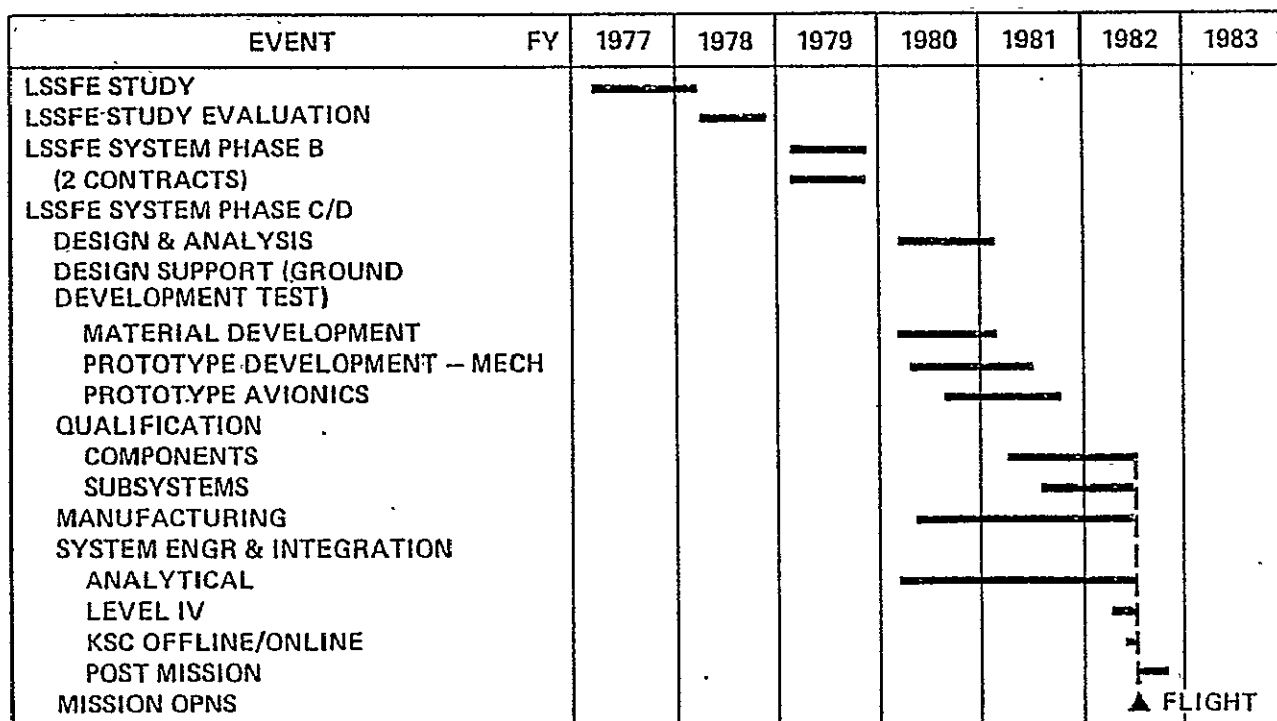


Figure 3-33. Preliminary LSSFE Program Schedule

Table 3-12. Preliminary LSSFE Development and Qualification Ground Test Program

Type/Purpose	Test
I. DEVELOPMENT (DESIGN SUPPORT)	
A. Material Development	
(1) To choose the correct materials, lay up configurations, and assembly to satisfy the design specification.	It is presumed that sufficient development work will already have been done to demonstrate that the design of the beam is substantially correct. These tests will be to optimize the final design and manufacturing requirements. Structural tests will be performed on samples of material lay ups to determine their structural characteristics. Measurements will be made of the thermal characteristics.
(2) To develop manufacturing criteria for design of the beam fabricator.	
B. Prototype Mechanical Systems 1 - <u>Forming (Beam Fabricator)</u>	
(1) To verify the function of the heating, rolltrusion, cooling sections.	(1) The equipment will be as near to final design as practical including drives, controls, and sensors. It will be operated to rolltrude caps and crossmembers of the configuration required for final assembly. Measurements will be made to confirm the power requirements, speed of rolltrusion, heating and cooling rates, etc. When the assembly is performing correctly, it will be placed in a vacuum chamber to demonstrate its function in a space environment. Zero "g" simulation will not be required. Consideration should be given to exposing the equipment to a vibration environment.
(2) To verify the parts are manufactured to design requirements.	
	(2) Structural, dimensional and NDT tests of the parts will be used to verify the manufacturing process.

Table 3-12. Preliminary LSSFE Development and Qualification Ground Test Program (Cont'd)

Type/Purpose	Test
I. DEVELOPMENT (DESIGN SUPPORT) (Cont'd)	
B. Prototype Mechanical Systems (Cont'd)	
2 - <u>Assembly (Beam Fabricator)</u>	
(1) To verify the function of the assembly section.	(1) The equipment will be as near to final design as practical including the drives, controls, and sensors. It will be operated to assemble the caps, crossmembers, and diagonal cords. Measurements will be made of the power requirements, speed of operations, etc. The machine will be placed in a vacuum chamber in a vertical or horizontal orientation to demonstrate its function in a space environment. Zero "g" simulation will not be required, although the assembly may be supported if the beam is rolltruded in the horizontal position. Consideration should be given to exposing the equipment to a vibration environment.
(2) To verify the parts are manufactured to design requirements.	(2) Structural, dimensional, and NDT tests of the parts will be used to verify the manufacturing process.
3 - <u>Cutoff (Beam Fabricator)</u>	
(1) To verify the function of the cutoff section.	(1) The equipment will be as near to the final design as practical including the correct drives, control and sensors. The cutoff will be operated to shear the elements produced in B-1 and the beams assembled in B-2 above. The operation of the equipment will be observed and measurements will be observed and measurements made of power inputs, etc.
(2) To verify the parts are cutoff to design requirements.	(2) The cutoff sections will be examined for the characteristics of the cutoff edges to determine if crushing or deformation is present, or if edge cracks are induced.

Table 3-12. Preliminary LSSFE Development and Qualification Ground Test Program (Cont'd)

Type/Purpose	Test
I DEVELOPMENT (DESIGN SUPPORT) (cont'd)	
B. Prototype Mechanical Systems (Cont'd)	
4 - <u>Beam Specimen</u>	
To determine the characteristics of the the assembled beam	(1) An assembled beam segment will be subjected to bending, compression, tension and torsion tests to determine its characteristics. (2) An assembled beam segment will be used for thermal-vacuum tests to determine its thermal deformation in a space environment. (3) An assembled beam segment will be used for modal survey testing. (4) Re-entry vibration test - requirement TBD.
C. Prototype Avionics System	
1 - <u>Beam Fabricator Controls</u>	
(1) To assist in the development of the choice of the control system components, and system design. (2) To demonstrate the feasibility of the control system.	(1) The development will include computer simulations, hybrid hardware/computer tests, and breadboard mockups of the control system. These tests will progress to the point that prototype control units can be fabricated and demonstrated. The off-the-shelf hardware will require little validation testing, but entirely new hardware should be demonstrated under the Space Shuttle induced and space natural environments. (2) Ideally, the hardware will be available for use in the beam fabricator prototype tests above, so that it can actually be used to control the beam building processes automatically, where feasible.

Table 3-12. Preliminary LSSFE Development and Qualification Ground Test Program (Cont'd)

Type/Purpose	Test
I DEVELOPMENT (DESIGN SUPPORT) (Cont'd)	
D. Support Equipment	
The avionics equipment and software should be tested in conjunction with the avionics tests under C above.	
II QUALIFICATION	
A. Components	
1 - <u>Mechanical</u>	
2 - <u>Electrical</u>	
3 - <u>Avionics</u>	
To verify suitability of production parts to perform satisfactorily in a space environment.	The components should be qualified to the required Mil Spec, such as MIL 1540-A. Components should be qualified to satisfy the environments anticipated during ground handling, Shuttle ascent/descent, and on-orbit assembly and deployment. The tests to be considered are functional, thermal-vacuum, thermal cycling, pyro shock, acceleration, humidity, pressure, leak, EMC, life, and other special tests.
B. Subsystems/Assemblies	
1 - <u>Beam Fabricator</u>	
To qualify the beam fabricator.	
(1) To operate as a mechanism.	(1) The beam fabricator will be tested in its entirety in a one-g environment to insure it operates correctly as a mechanism. Following a successful readiness checkout, it will be installed in a vacuum chamber and operated. The tests will include measurement of power requirements, fabrication speed, etc. It is assumed the component tests will have qualified the components so that the demonstration of function will suffice for qualification. It may be desirable to perform some modal and structural tests to yield data for analysis of suitability to meet the Shuttle and other spec requirements. The testing will be in the automatic mode so as to demonstrate the control system assemblies.
(2) To manufacture beams meeting the design specification.	

Table 3-12. Preliminary LSSFE Development and Qualification Ground Test Program (Cont'd)

Type/Purpose	Test
II QUALIFICATION (Cont'd)	
1 - <u>Beam Fabricator</u> - (Cont'd)	(2) The beams produced should be tested to insure they will meet the design specifications. A rerun of the tests of Section I-B-4 will be performed.
2 - <u>Beam</u>	A beam will be used for structural loading, modal survey, and simulated solar heating tests.
3 - <u>Grappler Assembly</u>	
To qualify a grappler assembly.	The testing will be a structural evaluation. Components will have been tested under II-A above.

3.3.2. PRELIMINARY COST ANALYSIS

Introduction

The results of this cost analysis of the LSSFE are presented and documented herein. This cost data represents preliminary top level estimates that can only reflect the program definition work performed to date and therefore cannot be considered complete or final. It does, however, represent a reasonable estimate based on information available at this time and is usable for planning purposes.

Work Breakdown Structure (WBS)

The preliminary WBS for the LSSFE program is shown in Figure 3-34.

Groundrules and Assumptions

The general groundrules and assumptions established for this cost estimate are as follows:

1. Costs are estimated in current/constant FY'77 dollars.
2. Costs are estimated for nonrecurring (development), recurring production (unit flight hardware), and recurring operation phases.
3. The costs include all experiment payload related costs through the launch and nominal 7 day flight of the fabrication experiment.
4. The flight will occur in FY 1982.
5. Prime contractor fee is not included in these estimates.
6. The Shuttle User Charge is assumed to include all Shuttle related activities such as on-line payload installation (OPF), MOC activities, flight crew costs and other common ground/mission operations and activities.
7. Pallet User Charge and Shuttle Mission Peculiar Support Equipment (2nd RMS) are TBD and not included in the current estimate.
8. Phase B study costs are not included.
9. The program estimated is defined in Section 2 above (LSSFE Program Definition for Cost Estimation).
10. This cost data is provided for planning purposes only.

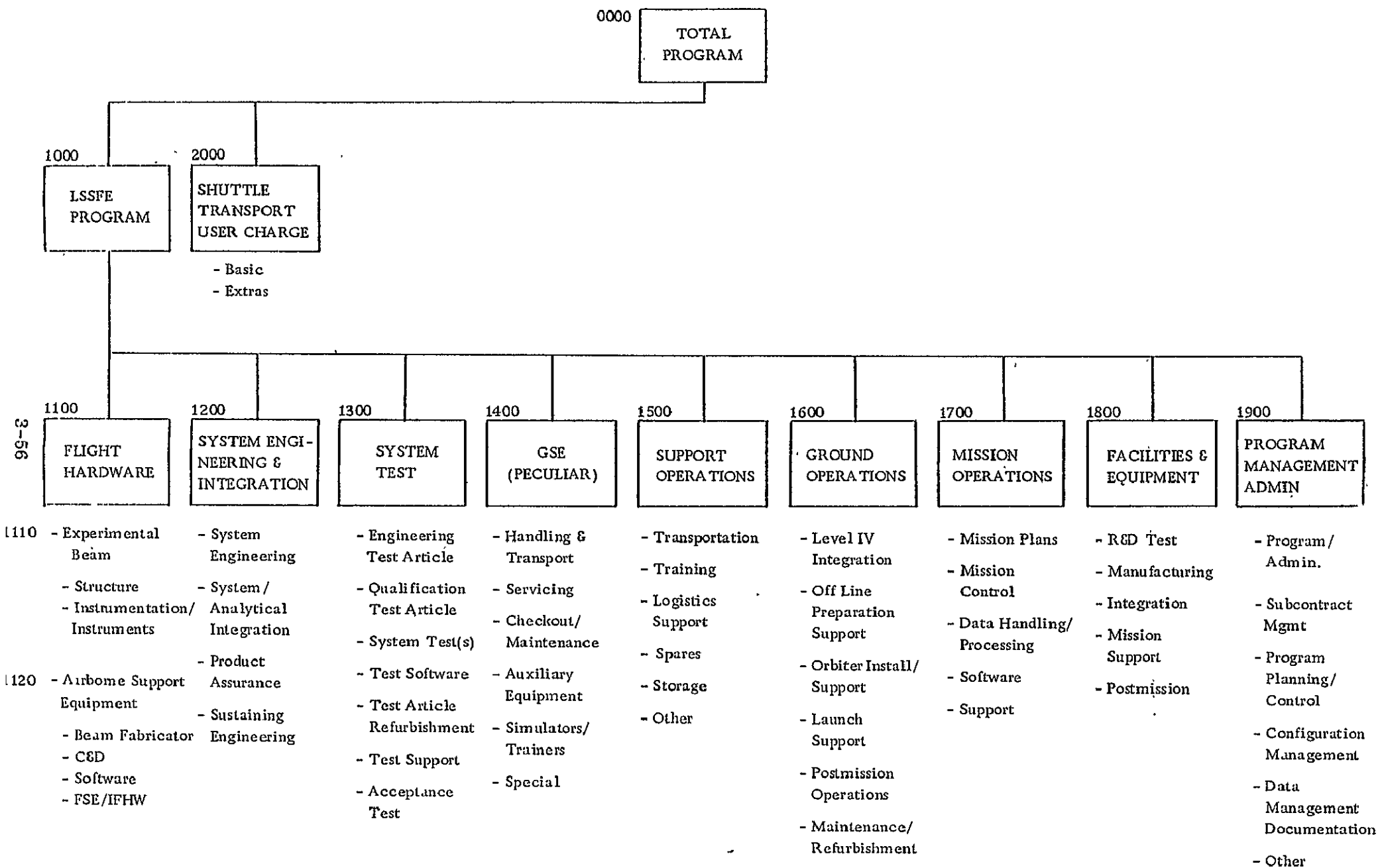


Figure 3-34. LSSFE Program Work Breakdown Structure.

Cost Estimate

A summarized cost estimate is presented in Table 3-13. As may be seen, a total program cost of about \$16.5M has been estimated exclusive of the Shuttle transportation user charge.

A second level cost breakdown is shown in Table 3-14. Specific assumptions made, relative to the LSSFE, for purposes of this estimate are included below.

1. It is assumed that three complete units are produced, 1) an engineering test unit, 2) a qualification unit refurbishable to a backup flight unit, and 3) the primary flight unit.
2. Fabrication experiment hardware weights are assumed to be those in Section 2.
3. Pitch fiber was assumed for the composite material and a conservative cost of \$50/lb was used.
4. Orbiter baseline aft flight deck controls and displays equipment are adequate and no additional equipment (or interface equipment) is necessary.
5. All software development for beam fabricator is included in the development cost for those items.
6. It is assumed that all flight support equipment and interface hardware requirements are satisfied by the basic design and no additional equipment is required.
7. Cost for refurbishment of the qualification article to flight backup configuration is included.
8. Minimum GSE development is assumed with the majority of the avionics and electronics checkout GSE being off-the-shelf.
9. Minimum spare and repair parts are assumed (components will be repaired and parts will also be available from the backup unit).
10. Transportation for trips, San Diego to MSFC, MSFC to KSC, and KSC to MSFC is TBD.
11. Ground Operations assumes 1) "Level IV" integration activities at MSFC, and 2) off-line preparation, on-line Orbiter installation and postmission removal at KSC.
12. Mission operations includes both a 7-day launch/orbital operations period and a

Table 3-13. Preliminary LSSFE Program Cost Estimate
(Millions of 1977 Dollars)

	NONRECURRING (DEVELOPMENT)	RECURRING (PRODUCTION)	RECURRING (OPERATIONS)
FLIGHT HARDWARE			
EXPERIMENTAL BEAM	.40	.13	—
AIRBORNE SUPPORT EQUIPMENT BEAM FABRICATOR	6.70	1.93	—
SYSTEM ENGINEERING & INTEGRATION	1.07	—	—
SYSTEM TEST HARDWARE	3.54	—	—
SYSTEM TEST/SUPPORT	.94	.10	—
GSE (PECULIAR)	.36	—	—
SUPPORT OPERATIONS	—	—	.24
GROUND OPERATIONS	—	—	.19
MISSION OPERATIONS	.05	—	.07
FACILITIES	—	—	—
PROGRAM MGMT/ADMIN	.65	.11	.03
SUBTOTAL	13.71	2.27	.53
TOTAL	—	16.51	—
SHUTTLE USER CHARGE*	—	—	9.95
PROGRAM TOTAL	—	26.46	—

*PALLET AND ORBITER MPE CHARGES TBD

1100	FLIGHT HARDWARE
1110	Experimental Beam
1111	Beam Structure
1112	Instrumentation/Instruments
1120	Airborne Support Equipment
1121	Beam Fabricator
1122	Controls & Displays
1123	Software
1124	Test Instrumentation/C&D
1125	FSE/IFHW
1200	SYSTEM ENGINEERING & INTEGRATION
1210	System Eng/Sustain Engineering
1220	System Integ/Analytical Integ.
1230	Product Assurance
1300	SYSTEM TEST
1310	Engineering Test Article
1320	Qualification Flt Backup/Article
1330	System Test Ops
1340	Test Software
1350	Test Article Refurb
1360	Test Support
1370	Acceptance Test
1400	GSE (PECULIAR)
1500	SUPPORT OPS
1600	GROUND OPS
	Analytical Integration Support
1610	"Level IV" Integration (MSFC)
1620	Off Line Preparation (KSC)
1630	Orbiter Installation Launch (KSC)
1640	Post MSN OPS
1650	Maintenance/Refurb (Post Flt)
1700	MISSION OPERATIONS
1710	Mission Control
1720	Data Handling/Processor
1730	Software
1740	Support
1800	FACILITIES
1810	Dev/Test/Mfg
1820	Integration (MSFC)
1830	Integration (KSC)
1840	Mission Support
1850	Post Mission
1900	PROGRAM MANAGEMENT/ADMIN.

2000	Shuttle Transportation
* Included in 1121	
** Included in 1200	GRAND TOTAL

13. No cost for postflight refurbishment of spaceborne equipment is included.

Annual Funding Needs

The preliminary program annual funding needs for the Phase C/D period are shown in Figure 3-35. A peak funding requirement of less than \$8M is shown for FY 1981.

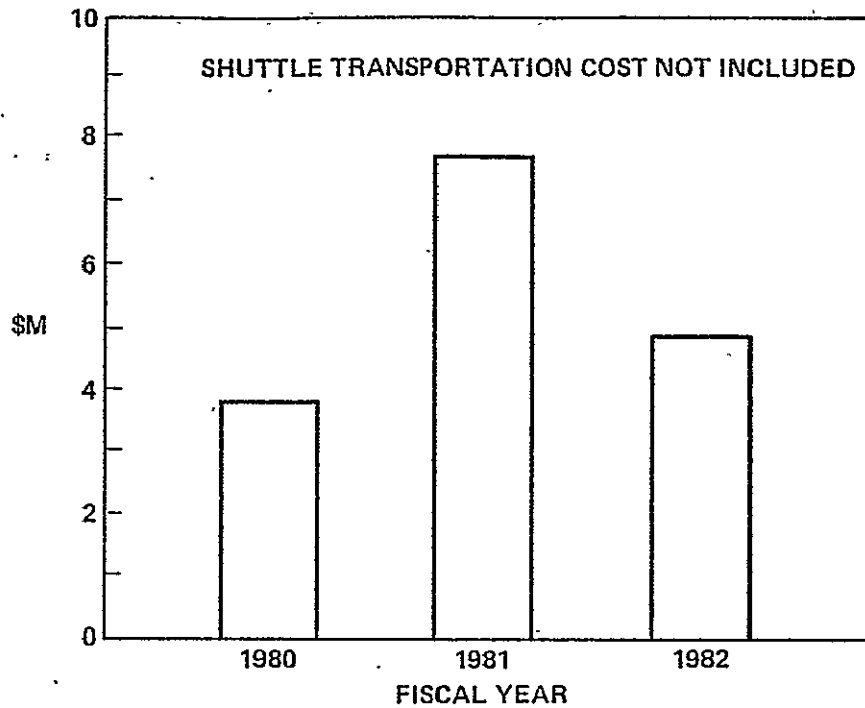


Figure 3-35. Program Annual Funding Needs
(1977 \$M)

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SECTION 4

MACHINE PREDESIGN FOR GROUND OPERATION

The machine predesign task objective was the functional and physical definition of a suitable prototype fabrication machine for ground operation. The purpose of ground operation would be the development of the new technology processes and applications essential to the successful and reliable fabrication on orbit of large graphite/thermoplastic space structures.

The beam fabrication machine developed for ground operation must of necessity be as functionally, physically, and operationally similar as possible to its in-space counterpart in order to assure applicability of results. This guideline has been implemented throughout the predesign task. Differences between flight and ground machines are confined to operational redundancy and flight-rating aspects. Upgrading of the ground machine to flight condition is entirely feasible.

4.1 DESIGN PARAMETERS

4.1.1 GENERAL REQUIREMENTS. These predesign requirements apply to the physical and functional definition of a prototype fabrication machine that can be ground operated in vacuum to demonstrate the practicability of manufacturing large graphite/thermoplastic structural trusses on orbit.

The beam fabrication machine developed for ground operation will be as functionally and operationally similar as possible to the flight experiment version. These requirements are established to attain this similarity and ensure early verification of this fabrication approach and a capability to upgrade the ground machine to flight status. The ground operation machine will be configured to produce the same one-meter-deep beam as the Orbiter-attached flight test experiment. The maximum fabrication rate is determined by Shuttle constraints. Manufacturing tolerances are derived from tentative full-scale construction criteria; e.g., for a solar power station. Since the ground test machine is essentially a Shuttle flight-test prototype, many of its physical characteristics are dictated by Shuttle interface requirements. It must be designed: to permit test verification in hard vacuum; to operate under zero gravity conditions; and to withstand non-operating exposure to the Shuttle launch environment.

Because cost is an important design parameter, target cost goals have been established for the machine design, manufacture and ground test program.

4.1.2 FABRICATION CAPABILITY.

4.1.2.1 The machine shall fabricate a triangular cross section truss from pre-processed graphite thermoplastic (GTP) strip material stored on reels. The machine shall provide the operations and equipment necessary to assemble truss elements (e.g., cross members to cap sections) and cut the truss to required length. Truss dimensions are given in Figure 4-1.

4.1.2.2 The truss fabrication process shall produce a completed beam at a minimum average rate of 0.018 m/sec. (0.7 in/sec). A maximum average rate of 0.05 m/sec (2 in/sec) shall be a design goal.

4.1.2.3 The completed beam twist error shall be controlled to ± 520 microradians (2 minutes) per bay by the fabrication process, and ± 520 microradians overall by selective twist control, if required.

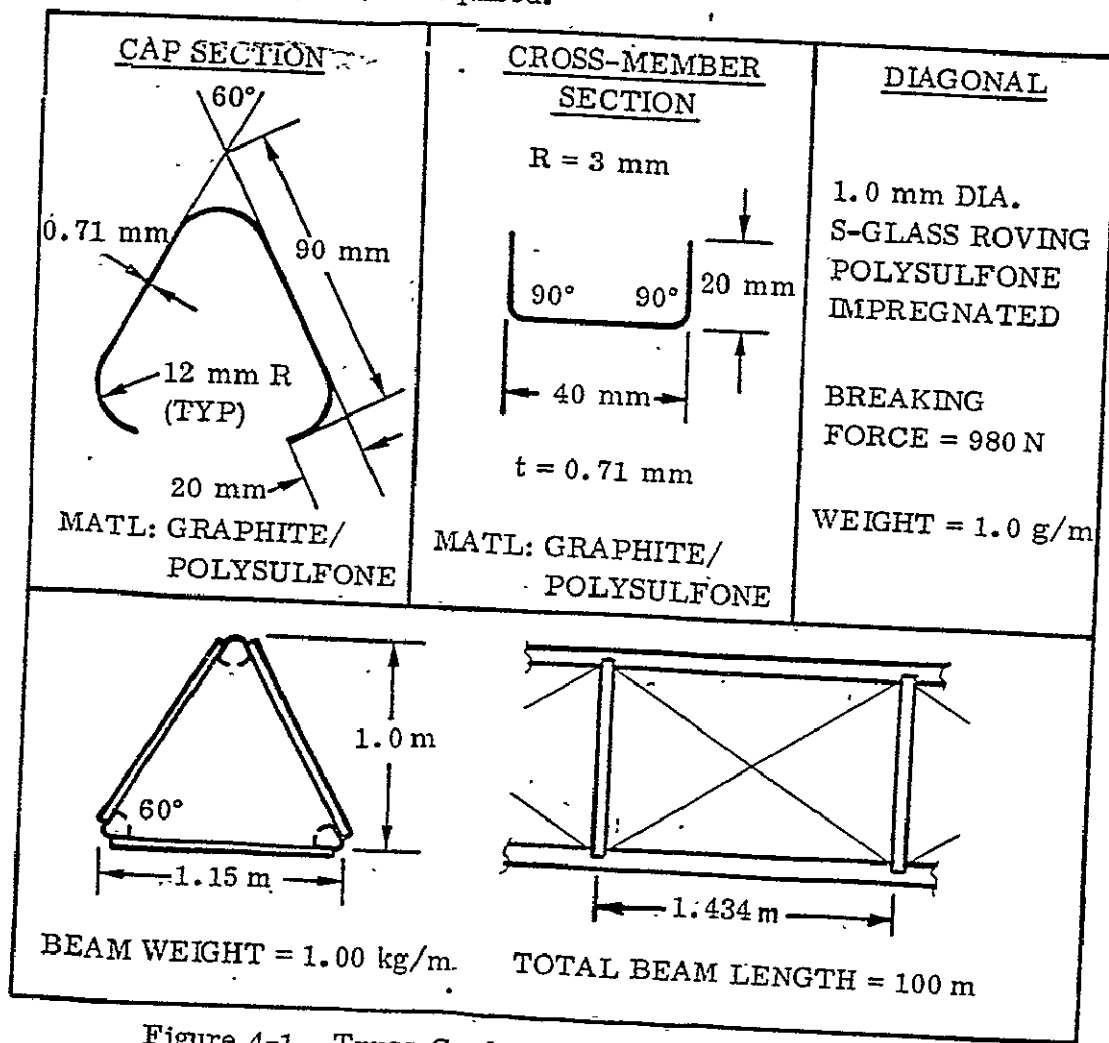


Figure 4-1. Truss Configuration Requirements Data

4.1.2.4 The completed beam overall straightness (bow) shall be controlled to four parts in one thousand (160mm in 100m) measured at the cap section heel under isothermal and unloaded conditions.

4.1.2.5 The feed section shall store and feed the flat strip stock material and prevent unwinding of the material during all phases of operation.

4.1.2.6 Material shall be graphite fiber, thermoplastic resin based composite. The stored flat strip stock used for cap and cross member sections shall be as follows:

Width:	190 mm (7.5 in.) (cap) 76mm (3.0 in.) (cross member)
Thickness:	0.71 mm (.028 in.)

4.1.2.7 Storage reels shall accommodate the material specified in sufficient length to produce a complete truss up to 100m in length.

3.1.2.8 The heating and guiding section shall heat and monitor the temperature of the GTP material before it enters the forming section. It shall be equipped with necessary guides to provide smooth low friction flow of material from the feed reel to the forming section.

4.1.2.9 Heat shall be concentrated on the bend zones of the material. Heaters shall raise the temperature of each bend zone from its assumed prevailing input temperature of $\sim 255\text{K}$ (0F) to the required temperature $490 \pm 15\text{K}$ ($425 \pm 25\text{F}$).

4.1.2.10 The heating and guiding section shall be thermally insulated to limit heat loss to 12% maximum from all sources during stabilized operation in space.

4.1.2.11 Power overload devices shall shut down the heaters and the process in the event of a malfunction.

4.1.2.12 Heater controls shall provide digital (on-off) operation of heaters as a function of material temperature limits and state of operation. Heaters along each fold line shall be independently controlled as a function of material temperature. The heater is turned off when the material approaches the required temperature. High temperature override protection is required, based on temperature and temperature rate.

4.1.2.13 Heater controls shall be designed to fail "off".

4.1.2.14 A sensor shall be provided at the entrance to the heating and guiding section to shut down the process drive and heaters at the end of the drive cycle when the end of the material strip passes by.

- 4.1.2.15 The forming section shall form the cap or cross member to the required cross section configuration. Additional heaters within the forming section shall preheat the material bend zones for system start-up. The heaters will also maintain material temperatures along each fold line during system operation.
- 4.1.2.16 The forming section shall have provisions for manual feed through of leader material for initial loading. Heating and cooling may be manually sequenced during ground loading operation.
- 4.1.2.17 The forming section shall be thermally insulated to minimize heat loss.
- 4.1.2.18 The cooling section shall cool the formed GTP section below the thermoplastic glass transition temperature. All cooling system equipment (e.g., pumps, reservoirs, regulators, etc.) that interface with the payload heat exchanger shall be provided by the flight experiment.
- 4.1.2.19 Cooling fluid shall be supplied at 280K (45F).
- 4.1.2.20 Cooling fluid shall be returned at 328K (130F) max.
- 4.1.2.21 Type of cooling fluid shall be Freon 21.
- 4.1.2.22 Cooling fluid flow rate shall be 0.25kg/sec. maximum.
- 4.1.2.23 The drive section shall provide the pull force on the material necessary to move the material from the feed reel through the entire process and beyond.
- 4.1.2.24 Drive section control shall provide necessary logic interlock to prevent drive unit activation when material temperatures or conditions are not ready for processing.
- 4.1.2.25 The drive section shall move all three cap sections in synchronism at all points of the required stroke.
- 4.1.2.26 Drive unit shall automatically shut off at end of required stroke.
- 4.1.2.27 Cross member section material stroke shall be controlled within ± 6 mm (± 0.25 in).
- 4.1.2.28 The cap members drive shall limit the beam acceleration to ± 130 mm/sec² (± 5.0 in/sec²).
- 4.1.2.29 The assembly section shall provide the necessary storage, dispensing, clamping and fastening functions to join the side members and diagonal bracing to the beam cap sections to form the completed beam.

4.1.2.30 The beam cutoff section shall provide a means to sever the completed beam at the required length.

4.1.2.31 Control of the cutoff function shall be by operator command.

4.1.2.32 Debris resulting from the cutoff function shall be eliminated or prevented from escape into the surrounding environment.

4.1.2.33 A process controller shall be provided to control the process in accordance with the requirements specified herein.

4.1.2.34 Process control shall provide necessary status monitoring lights and manual switching override controls at the Orbiter control station.

4.1.2.35 Synchronization of all machine functions shall be provided by electronic controls or mechanical devices.

4.1.3 SHUTTLE COMPATIBILITY (REF). The final application of space fabrication technology is the utilization in orbit of a space fabrication module or modules. Therefore specific design constraints will be considered in the ground demonstrator to permit future conversion to a flight article. These constraints are as follows:

4.1.3.1 The fabrication machine shall be capable of sustaining shuttle launch loads and operating in a space environment; i.e., under hard vacuum and zero gravity conditions.

4.1.3.2 Contamination of adjacent space vehicles (e.g., Shuttle Orbiter, Space Station, satellites) shall be eliminated or minimized. This relates to the release of fluids, lubricants, vapors, gases, and particles stemming from the fabrication process.

4.1.3.3 If contamination potential exists, special provisions for capturing contaminants shall be considered and utilized.

4.1.3.4 The fabrication machine shall be capable of operational attachment to a two-pallet Spacelab train in the Orbiter cargo bay.

4.1.3.5 In a stowed condition, the total fabrication experiment shall occupy less than half the cargo bay space; i.e., less than 15 feet diameter and 30 feet long. The experiment shall be compatible with launch, operation, and return in either the forward or aft half of the bay to the extent practicable.

4.1.3.6 In general, the fabrication machine shall be compatible with the document "Space Shuttle System Payload Accommodations" (JSC 07700, Volume XIV).

4.1.4 ENVIRONMENTAL CONSTRAINTS. The fabrication machine will accommodate flight article environmental design parameters to the extent necessary to permit ground test verification of the concept.

4.1.4.1 The fabrication machine shall withstand vibration resulting from acoustic spectra generated in the Orbiter cargo bay during ascent and entry.

4.1.4.2 The fabrication machine shall be protected from solar radiation to the extent necessary to assure satisfactory thermal control.

4.1.4.3 Coolant fluid piped into the machine for thermal control shall be of quantity and condition approximating that to be expected operationally.

4.1.4.4 The electrical power system shall be restricted in total energy draw to 7kW average and 12kW peak for fifteen minutes in any three-hour period. The use of 115 VAC rather than 28 VDC is permissible.

4.1.4.5 The electromagnetic compatibility needs of operational missions shall be considered.

4.1.4.6 Compatibility of machine controls accommodations to eventual operational requirements shall be considered.

4.1.4.7 The eventual safety needs of manned orbital operations shall be considered.

4.1.5 COST GOALS. As with all NASA-funded programs, cost is an important design parameter. The establishment of design-to-cost goals is an important guideline for downstream development. These goals are preliminarily set as follows for the ground fabrication machine program, subject to NASA approval (1977 dollars).

4.1.5.1 The cost goal for Design and Analysis shall be \$510K.

4.1.5.2 The cost goal for Procurement and Manufacturing shall be \$580K.

4.1.5.3 The cost goal for Test shall be \$160K.

4.1.5.4 The program cost goal shall be \$1310K.

4.1.5.5 Program duration shall be twelve months.

4.2 DESIGN APPROACHES

A ground operation beam fabrication machine has been predesigned to the requirements given in Section 4.1 above. Several alternative design approaches were

considered and these have been discussed earlier. In addition, alternative point solutions to each selected approach were developed. The least complex solution was chosen in each case that would meet requirements. Some solutions were driven by the physical interrelationships of the functional components when mounted to the basic structure.

4.2.1 GENERAL ARRANGEMENT. The recommended concept for the beam fabricator machine consists of a light weight strong back support structure with the following machine elements mounted on it:

1. Three cap section rolltruder assemblies.
2. Three cross member section rolltruder assemblies.
3. Three cross member transporter installations
4. Three diagonal cord dispenser installations.
5. Three ultrasonic welder mechanism installations.
6. Six beam support rollers (two at each cap section).
7. Three beam cutoff mechanisms (one at each cap section).
8. Six weld system 20k Hz power supplies.
9. Three heater interface switching units.
10. One temperature sensor signal conditioner.
11. One temperature sensor data multiplexer.

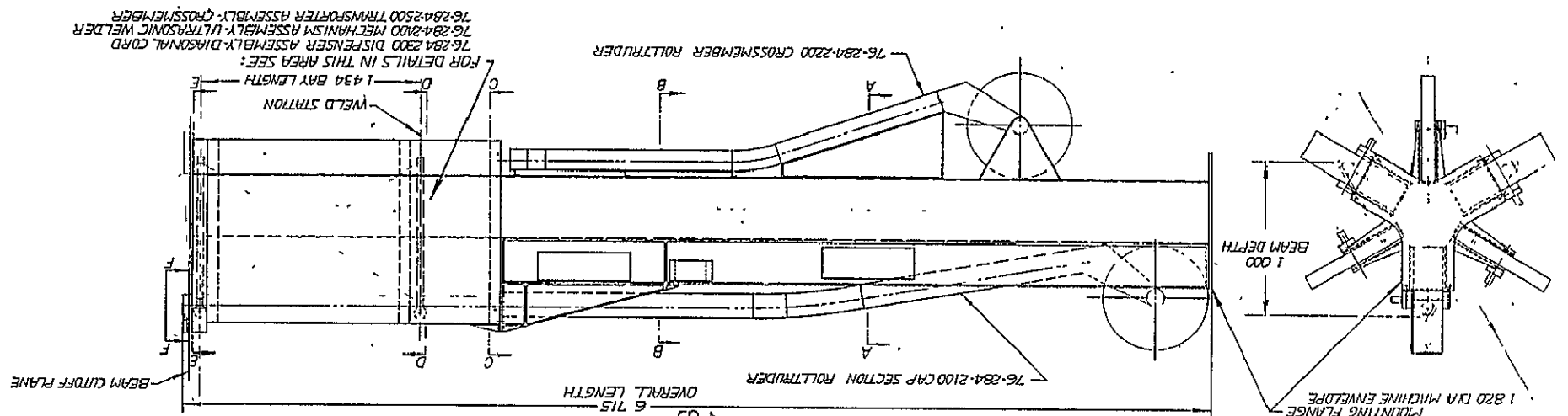
Figure 4-2 shows the general arrangement of the machine which will fabricate a continuous triangular beam 1.0 meter deep.

Description — The support structure has a mounting flange on one end that is suitable for attaching the machine to the ground test stand or a deployment trunnion in the Shuttle payload bay.

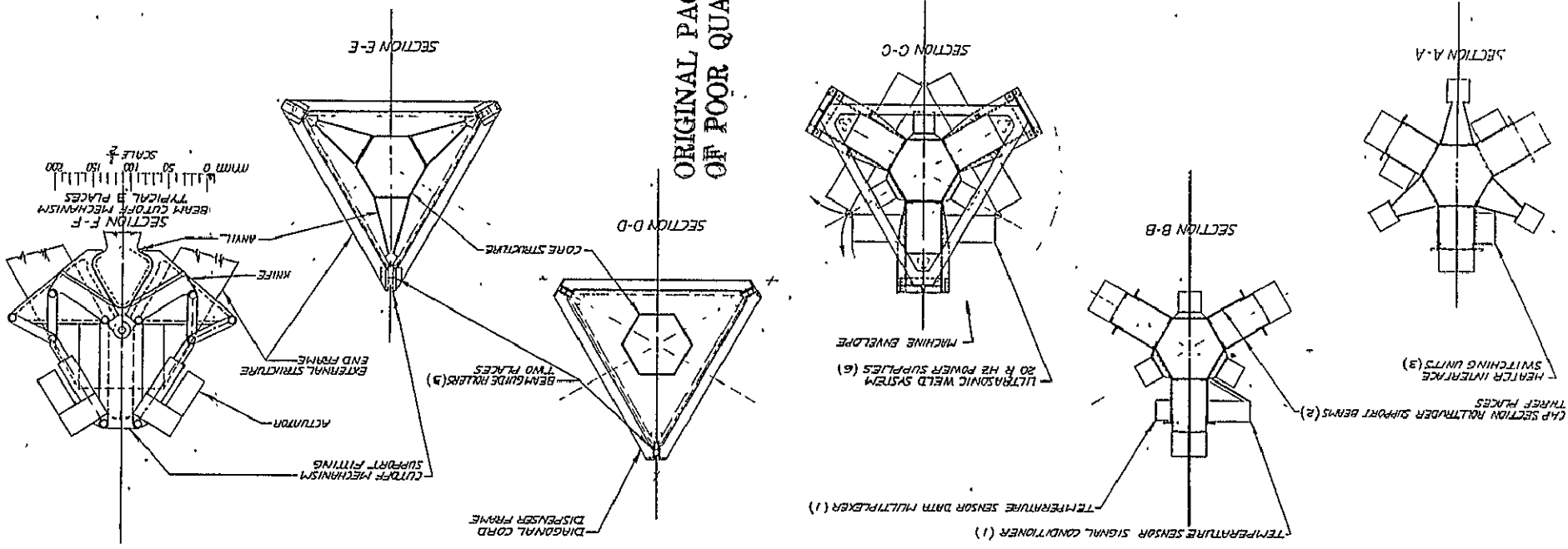
The mounting flange is attached to a hexagonal cross section core structure (420 mm across the flats) and three cap section rolltruder support beams attached to the core structure at 120° spacing. The three cap section rolltruders (Figure 4-3) are mounted on these beams and the three crossmember section rolltruders (Figure 4-4) are equally spaced between them. The heater interface switching units, temperature sensor signal conditioner, temperature sensor data multiplexer and six weld gun power supply units are mounted on the webs of the beams supporting the cap section rolltruders. The 6 630 mm long hexagonal core structure extends the full length of the beam fabrication machine and provides support for the cross member transporter installation (Figure 4-6), the weld gun hinge and anvil fittings (Figure 4-7) and the anvils for the beam cutoff mechanism (Section FF of Figure 4-2). A triangular external structure is attached to fittings on the ends of the cap section rolltruder support beams. The 2 015 mm long structure provides for installation of the beam support rollers, the diagonal cord dispenser frame (Figure 4-5) and the beam cutoff mechanisms are located at a point that permits cutting off a section of beam without disturbing the rigging of the machine to allow fabrication of several beam sections.

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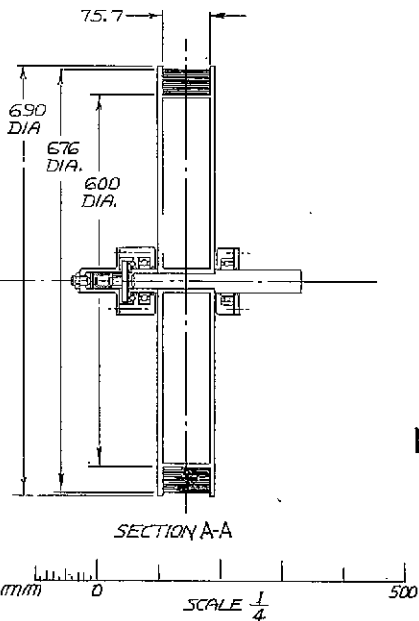
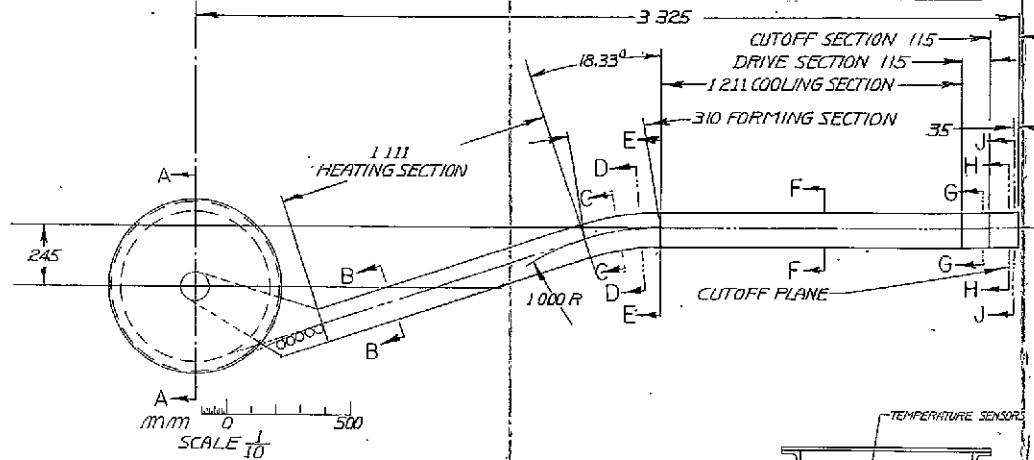
Operation — The beam cap section rolltruder drives move the cap sections one bay length (1434 mm) while each cross member rolltruder drive delivers the length (1111 mm) required for a cross member to the transporter and cuts it off. During this period the diagonal cord dispenser stingers align the cords for ultrasonic piercing of the cross members. Then the transporter delivers the cross member to the piercing position. The ultrasonic weld guns move to the intermediate position piercing the cross member and the cap section to hold the cross member in place with the piercing pins. The transporter returns to the receiving position as the diagonal cord dispenser aligns the cords in the weld position and tensions them over the piercing pins. The ultrasonic weld guns are moved to the fully engaged position and the cap sections, diagonal cords and cross members are fused together. The weld guns retract clear of the newly installed cross member and the cycle repeats until the length of beam desired has been generated. At this point the beam cutoff mechanisms are actuated to sever the beam caps and diagonal cords.

4.2.1.1 Cap Section Rolltruder — Figure 4-3 shows the general arrangement of rolltruder for forming the beam cap section.

Description — The machine element for forming the cap section consists of a long box frame with the reel for the laminate strip mounted at one end and the drive for pulling the laminate through the machine mounted at the other end. The reel (Section A-A Figure 4-3) has an adjustable drag brake on one hub and is hooded to contain the "clockspring" tendency of the laminate in the event of drag brake malfunction. A set of rollers that maintains a minimum bend radius of 300 mm from full to empty reel is located on the frame adjacent to the reel. Next to the rollers is the heating module (Section B-B) which is one beam bay (1434 mm) in length. The heat is confined to the bend zones in the laminate by using linear resistance heaters in parabolic reflectors.

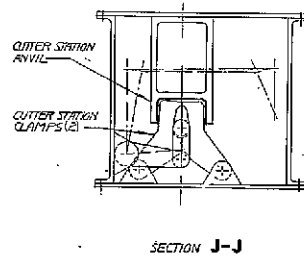
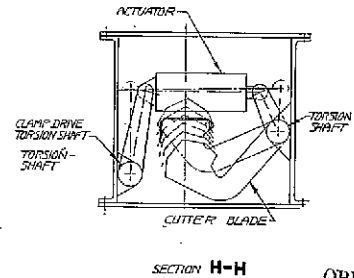
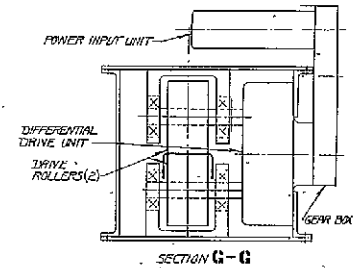
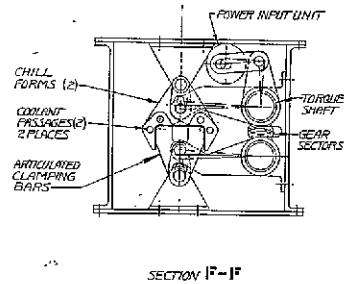
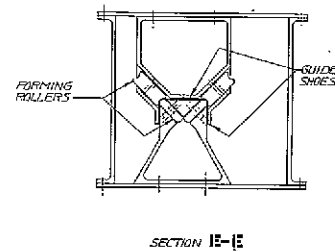
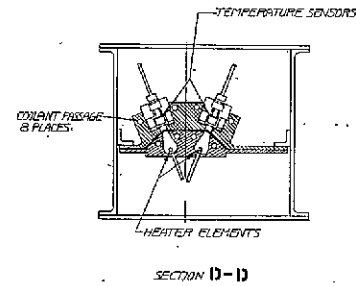
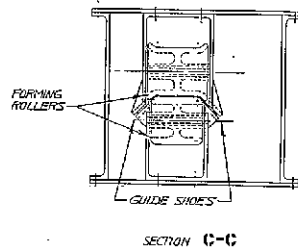
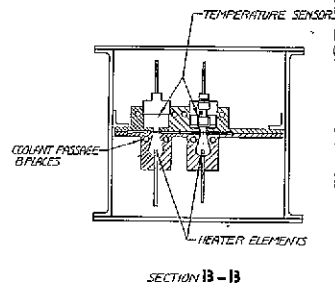
Coolant flowing through four passages in each heater block carries away the small amount of heat absorbed in the reflector.

Temperature sensors are installed on the opposite side of the laminate to provide feedback to the temperature control system. Coolant flowing through two passages provides thermal control of each sensor to assure a stabilized temperature reference. A forming module (sections C-C, D-D, E-E and F-F) consisting of a series of rollers and guideshoes interspersed with heaters is located immediately downstream of the heating module. The components in this module are placed on a curvature that has been carefully developed to coincide with the natural flow of the laminate during the forming process to avoid any wrinkling/malformation in the plastic bend zones that would damage the graphite fibers in the laminate. The laminate is formed to a Vee shape as shown in Sections C-C and E-E then the flanges are formed as shown in Section F-F. Heater elements similar to the arrangement shown in Section D-D are interspersed between each forming stage. Each linear heater set has a controlling sensor. The heaters in the heating



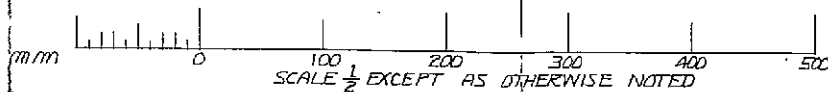
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FOLDOUT FRAME



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DESIGNED BY	TRACED BY	PRELIMINARY DESIGN DRAWING
PROJECT	DATE	FIGURE 4-4
GENERAL DYNAMICS		CROSS MEMBER ROLLTRUDER
Convair Aerospace Division		CODE IDENT. 14170
SAN DIEGO, CALIFORNIA		DRAWING NO. 76-284-2200
SCALE NOTED		SHEET 1 OF 1

and forming sections are controlled to provide a bend zone temperature of $425 \pm 25^{\circ}\text{F}$ in the forming section. The plastic bend zones are protected from scuffing by relief cuts in the guide shoes and teflon coating on the idler rollers.

The cooling module (Section G-G), consisting of two articulated external chill forms, three articulated internal clamping bars and an actuating mechanism, is 100 mm longer than the beam bay length to assure that the section is properly chilled by the time it leaves the cooling module. Coolant fluid flows through five passages located in the bend zone areas of each chill form. The mechanism is powered by an electrical linear actuator driving two torsion shafts mounted on the module sidewalls. The chill forms are attached to the torsion shafts 3 places (at 500 mm spacing) by links on one side and spring cartridges on the other. The torsion shaft linked by the spring cartridges is also linked three places by lost motion links and idler cranks to the clamping bar actuating plungers. This lost motion arrangement allows the chill forms to close before the clamping bar plungers move. The clamping bar mechanism plunger drives the apex bar through a spring to permit clamping the apex bar first and then "wiping" the side bars into place.

The drive modules of all three cap rolltruders are powered by a single source through a torque shaft arrangement.

Operation — The beam cap section fabrication is a step process that produces one bay length of cap section each step. The process consists of releasing the clamping bars and chill forms in the cooling section of all three cap section rolltruders. The beam fabrication machine then powers the cap section rolltruder drive modules to move the laminate strips one bay length. The chill forms and clamping bars reengage to cool the bend zones while the heating section brings the bend zones in the next bay length up to temperature.

4.2.1.2 Cross Member Rolltruder — Figure 4-4 shows the general arrangement of a rolltruder for forming and cutting off the beam cross member channels.

Description — The machine element for forming the cross member channels is very similar to the cap section rolltruder with the following variations:

1. The laminate width is reduced from 190.0 mm to 76.0 mm.
2. The number of bend zones is reduced from three to two.
3. The length of the heating section is reduced from 1434.0 mm to 1111.0 mm.
4. The length of the cooling section is reduced from 1534.0 mm to 1211.0 mm.
5. A cutoff module (sections H-H and J-J) is added.

The cutoff module consists of a cutter anvil, two cutter clamps, a cutter blade and an actuating mechanism powered by a linear electrical actuator. The actuator is

attached to bellcranks on two torsion shafts mounted on the module sidewalls. One shaft drives the cutter clamps and the other drives the cutter blades. A torsion spring on the cutter blade shaft delays rotation until the clamps are engaged.

Operation — The cross member rolltruder operation is identical to the cap section rolltruder operation except that its cutoff module clamps, cuts, and releases a section of channel to deliver it to the cross member transporter.

4.2.1.3 Diagonal Cord Dispenser — The pair of cords used for diagonal bracing between cross members on each face of the beam are fed, positioned and tensioned by the dispensing mechanism shown in Figure 4-5.

In addition to meeting the requirements of Section 4.1 this mechanism must

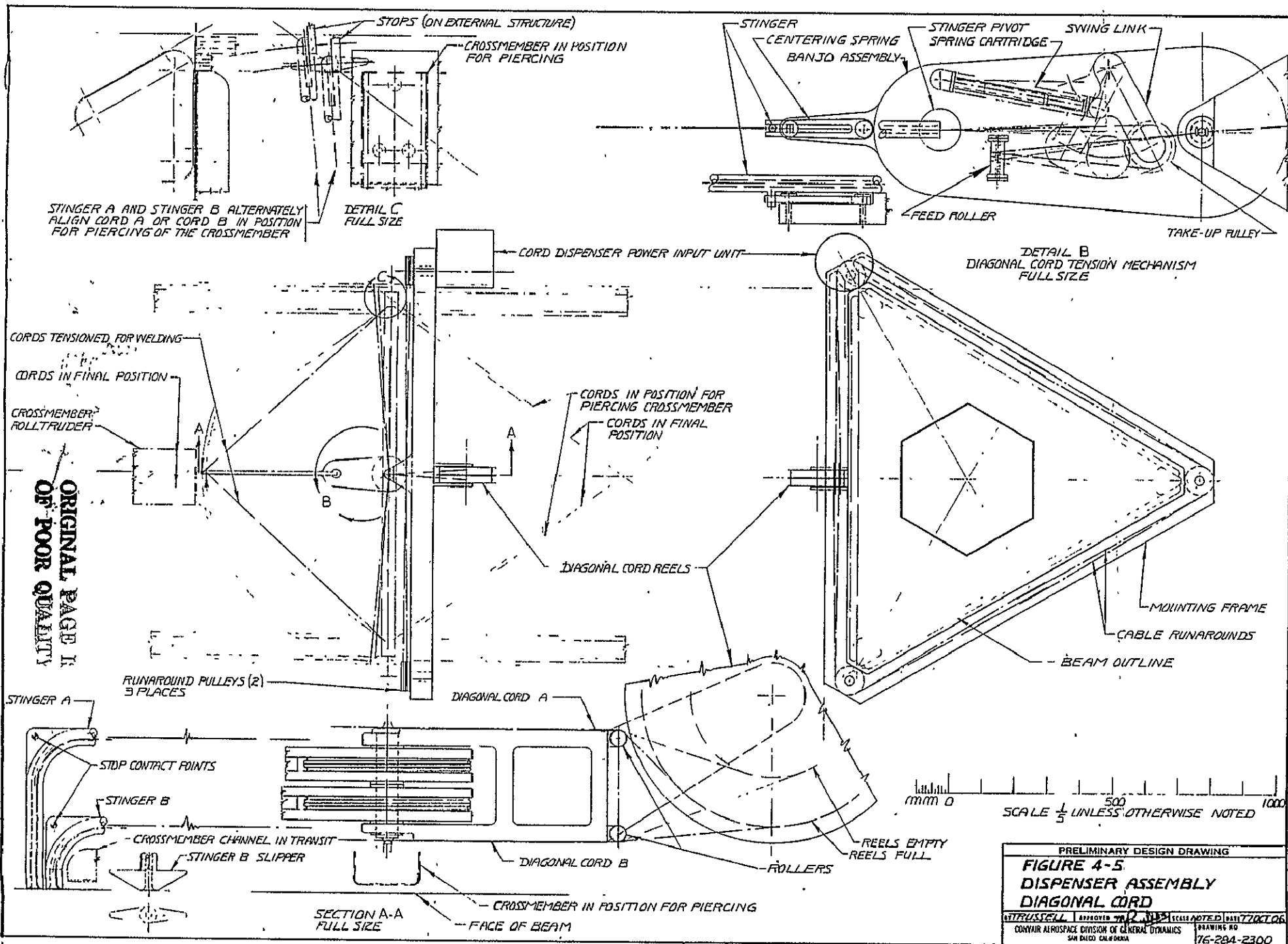
1. Store and feed the cords.
2. Position the cords for ultrasonic piercing of the cross member and cap section.
3. Position and tension the cords on the piercing pins for welding.

Description — The diagonal cord dispenser assembly consists of an external triangular frame located 100 mm "downstream" of the cross member weld station on which is mounted:

1. Three pair of storage reels for the diagonal cords.
2. Three pair of co-axially pivoted reciprocating dispensing arms.
3. Two runaround cable systems to actuate the dispensing arms.
4. One cord dispenser power input unit.

The dispensing arm pivots are located at the weld station above the mid-points of the cross members. The pivot pins have hardened cord guides at each end.

The dispensing arms consist of spring centered tubular stingers pivot mounted on the banjo assemblies (Detail B). Blades on the outer ends of the stingers provide contact points for stops on the external structure at the "piercing positions" (Section A-A and Detail C). The inside or lower stinger has a slipper to deflect the cord being dispensed by the outside stinger when they pass in transit (Section A-A). The cord tensioning mechanism consists of a feed roller and a takeup pulley on a spring positioned swing link (Detail B). The geometry and spring rate were selected to provide a nearly uniform tension of 80 to 90 newtons (18 to 20 lb) on the cord being fed into the stinger. When this tension is exceeded the spring cartridge bottoms and the cord reel brake controls the tension at a level of 135 to 150 newtons (30 to 34 lb). Each banjo assembly has a cable drum concentric with its pivot (Section A-A) which is connected to a runaround cable that drives the



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corresponding dispenser arms on each beam face. The cord dispenser power input unit drives the cable runarounds in opposite directions through cable drums mounted on coaxial shafts. The cord storage reels and brakes are mounted on the frame opposite the dispenser arm pivots.

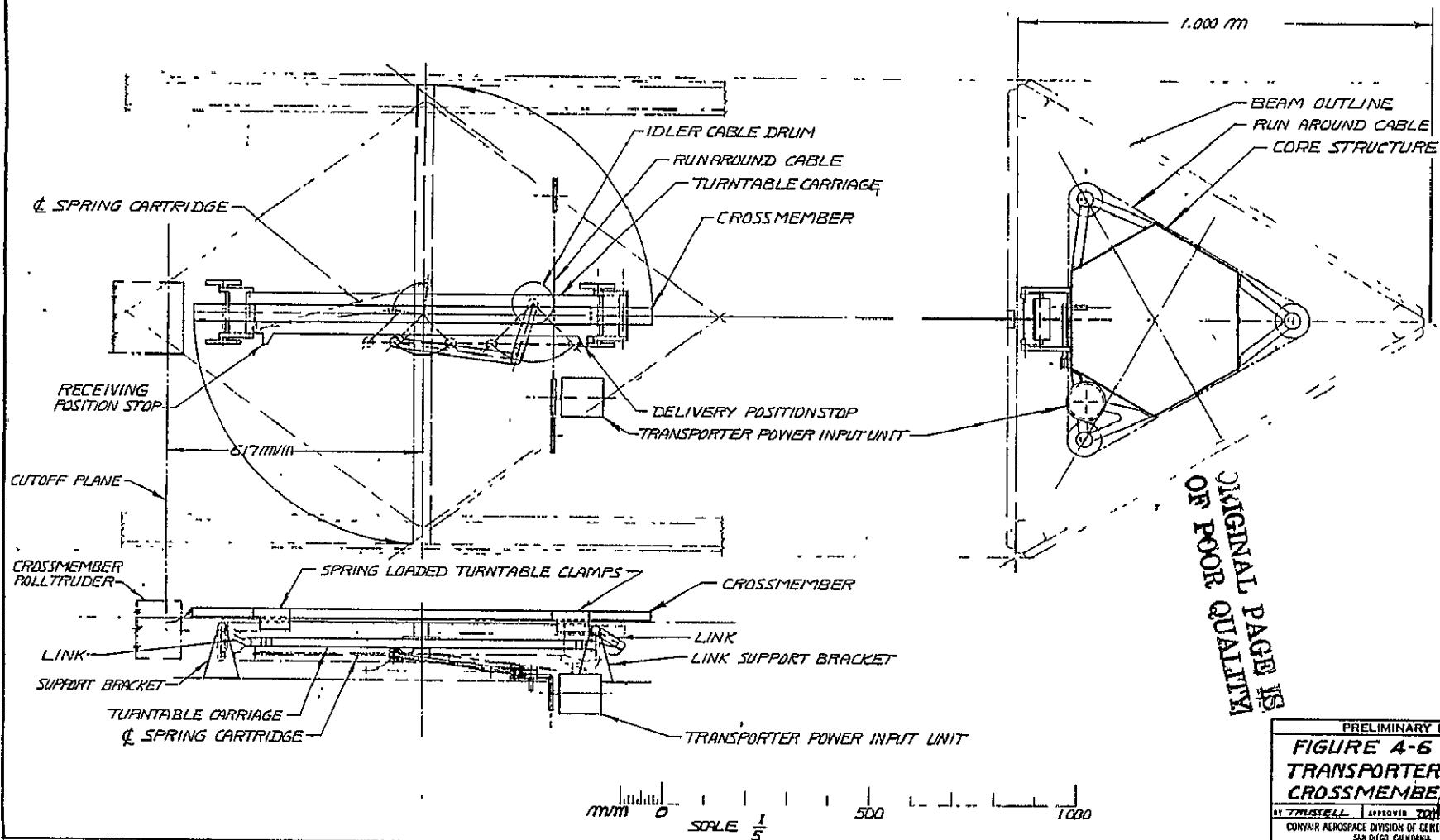
Operation — When the cross member weld is completed the dispensing arms swing to the piercing position as the beam advances paying out the cord under a 30 to 34 lb tension load. When the new cross member is secured in place with the piercing pins the power input unit swings the dispenser arms to the mid point and then reverses direction a few degrees to allow the takeup pulley in the tension mechanism to move approximately 30 mm from the stop position to reduce the cord tension to the proper level for welding. Since each pair of cords is installed in alternate diagonal positions in each succeeding bay, the effect of any disparities in tension load is likewise cancelled in each succeeding bay. When the weld is completed the cycle is repeated.

4.2.1.4 Cross Member Transporter Assembly — The cross member transporter moves the cut off member from the forming unit inside the beam envelope to the weld position outside the beam envelope.

In addition to meeting the requirements of Section 4.1 this mechanism must:

1. Receive cross member as it is rolltruded from forming machine inside the beam envelope.
2. Hold or secure the cross member to maintain control of it after cutoff.
3. Move the cross member to clear the cutoff unit.
4. Move the cross member to a position outside the beam envelope that will clear the diagonal cord during rotation to the weld position.
5. Rotate 90 degrees from the home position to the weld position.
6. Provide the resiliency required to permit the ultrasonic weld heads to depress the cross member against the cap section during the piercing operation.
7. Release the cross member now being held in position by the piercing pins and rotate back to the home position.
8. Move back to and precisely index with the cutoff module on the forming machine.

Description — The basic arrangement is a turntable mounted on a carriage platform suspended on four parallel links (Figure 4-6). The carriage is precisely indexed in the receiving position by the parallel links and a stop on one of the forward link support brackets at the docking end and in the delivery position by the links and a stop on one of the aft link support brackets. A turntable is pivot mounted on the carriage with a 6 mm freedom of motion in the axial direction (Figure 4-6). This motion is

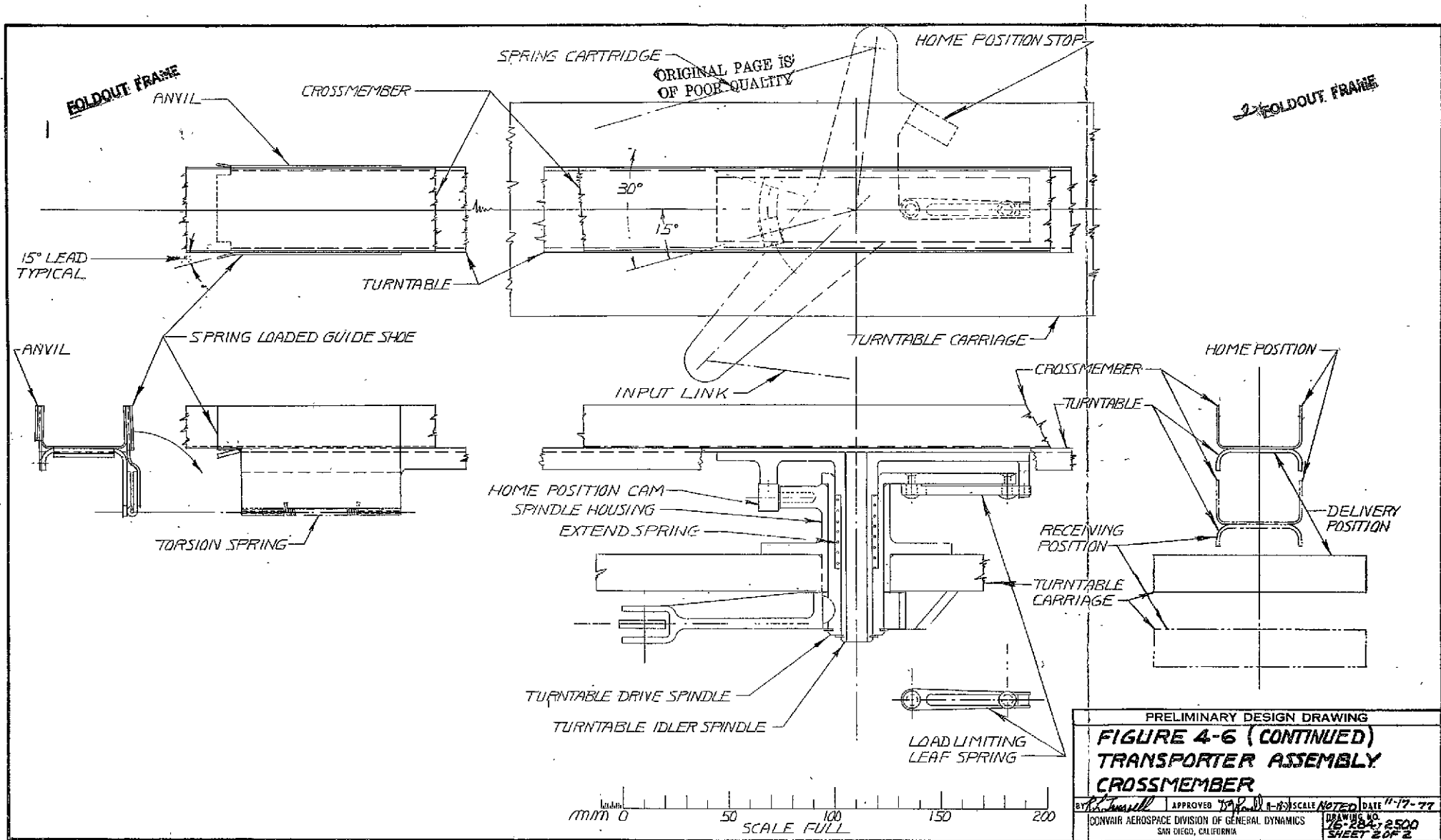


PRELIMINARY DESIGN DRAWING

FIGURE 4-6
TRANSPORTER ASSEMBLY
CROSSMEMBER

BY 77145/STELL APPROVED 77145/STELL SCALE 20% DATE 77102721
CONVAIR AEROSPACE DIVISION OF GENERAL DYNAMICS DRAWING NO. 76-294-2500
SAN DIEGO, CALIFORNIA 1st OF 2

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PRELIMINARY DESIGN DRAWING			
FIGURE 4-6 (CONTINUED)			
TRANSPORTER ASSEMBLY			
CROSSMEMBER			
BY <i>[Signature]</i>	APPROVED <i>[Signature]</i>	SCALE <i>NOTED</i>	DATE 11-17-77
CONVAIR AEROSPACE DIVISION OF GENERAL DYNAMICS SAN DIEGO, CALIFORNIA			DRAWING NO. 16-284-2500 SHEET 2 OF 2

controlled by a cam which provides for positive extension of the turntable in the home position. A weak coaxial spring in the pivot shaft provides a small force to maintain the turntable in the extended position during rotation from the "home" to the "weld" position. A "U" shaped leaf spring is installed in series between the turntable idler spindle and the turntable drive spindle to simplify rigging and prevent excessive loads when the turntable contacts its stops. A double lobed bellcrank is attached to the drive spindle below the carriage. The lobe with the stop pad on it is attached to a spring cartridge the other end of which is also attached to the carriage. The force exerted by this cartridge prevents rotation of the turntable drive spindle until the carriage force against the delivery stop exceeds 22 newtons (5 lb). A stop on the bottom of the carriage resists the force of the spring cartridge in the "home" and "receiving" positions.

The turntable is an inverted channel mounted on the idler spindle with a spring loaded clamping arrangement at each end which consists of an anvil on one side and a torsion spring loaded guideshoe on the other side with the hinge line located 30 mm below the turntable surface. Fifteen degree lead angles are provided on all "upstream" edges to assist the feed guides during loading. The transporter at each beam face (3) is connected to a common runaround cable system by linking it with a bellcrank attached to an idler cable drum supported by the beam fabricator core structure.

The runaround cable system is actuated by the power input unit mounted on the beam fabricator core structure. This unit mechanically programs the rotary power input from the beam fabricator prime mover to synchronize the transporter with the other beam fabrication functions.

Operation -- As the cross member rolltruder drive advances material to form another increment of channel it loads the previously formed section into the transporter which is docked at the cutoff module. The cross member is guided into the spring loaded clamps on the transporter turntable which are deflected to receive and grip it. When the rolltruder has measured the correct length of channel for a cross member into the transporter, it stops and the cross member is cutoff. The transporter drive is then actuated to rotate the bellcrank attached to the cable drum. The first motion of this bellcrank swings the carriage on parallel links to the delivery position stop.

The spring cartridge on the carriage prevents turntable rotation until the delivery position stop reaction builds up enough moment at the drive spindle bellcrank to overcome the spring force. The cable drum bellcrank continues to rotate and now moves the drive spindle 90° to bring the cross member into the position at the weld station. At this point the transporter drive pauses to permit the ultrasonic weld heads to pierce the channel and cap strip. During piercing the weld head force overcomes the weak

coaxial spring in the turntable and moves the cross member down approximately 5 mm to the beam face. After the cross member is secured by the weld gun piercing pins the transporter drive is actuated to return the turntable to the docking position. The first part of the turntable rotation cams the clamps open to release the crossmember and the last 30° of rotation cams the idler spindle and turntable to the extended position. When the turntable reaches the home position the drive spindle bellcrank is against the stop and the continuing motion of the transporter drive swings the carriage to the docking position ready to receive another cross member section.

4.2.1.5 Ultrasonic Welder Actuation System — The end of each beam bay is completed by welding a pair of diagonal cords and a cross member to each of the three beam faces with six weld guns actuated by the system defined in the following paragraphs. (See Figure 4-7.)

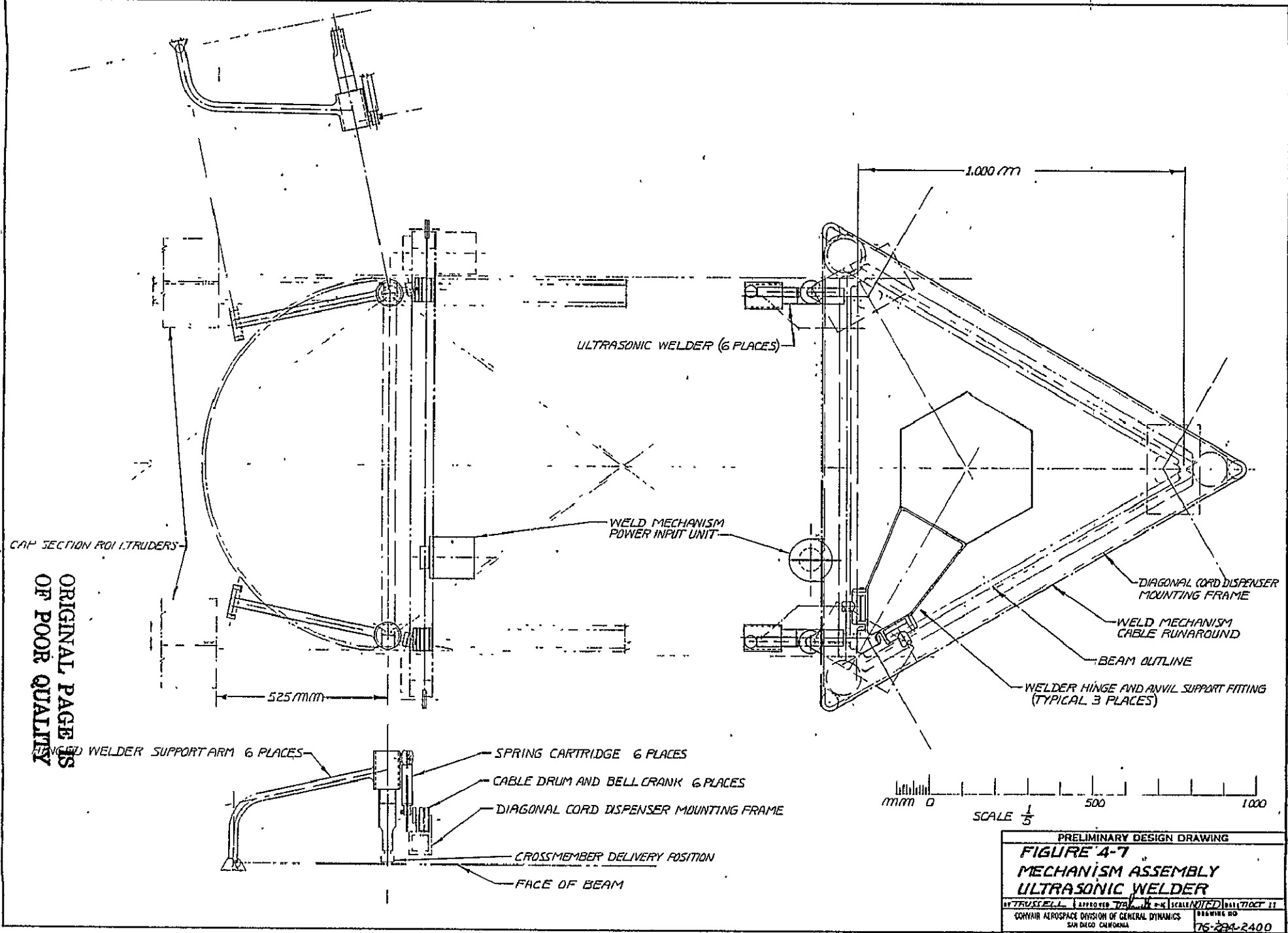
In addition to meeting the requirements of Section 4.1 the ultrasonic weld gun actuating mechanism must:

1. Move the weld guns to an intermediate position that enables the piercing pins on the weld guns to penetrate the cross members and cap sections.
2. Pause at this intermediate position while the cross member transporter returns to the home position and the cord dispenser aligns and tensions the cords in the weld position.
3. Move the guns to the weld position and maintain a 90 to 100 pound force on each gun during the weld operation to insure an efficient transfer of energy into the faying surfaces at the welds.
4. Move the weld guns back to a retracted position that will clear the beam when it is advanced.

Description — Each weld gun is installed in a support arm attached to the internal structure with a hingeline located in the plane of weld to provide forces normal to that plane. Three anvils are also mounted on the internal structure to react the weld gun forces. The actuation mechanism consists of the following components which are mounted on the diagonal cord dispenser frame:

1. One weld mechanism power input unit
2. One runaround cable system
3. Six spring cartridge links with spherical bearings in each end.

A cable drum driven bellcrank assembly is located at each weld gun and connected to the weld gun support arm with a spring cartridge link. The cable runaround is arranged around the cord dispenser frame connecting the cable drums on the power input unit and bellcranks.



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Operation — When the cross member is in place the process control unit commands the weld mechanism power input unit to the "pierce position" rotating the bellcranks at each weld gun to that position. The guns move until the piercing pins come into contact with the cross members forcing them against the diagonal cords and beam caps with the balance of the motion being absorbed by the spring cartridges. The control unit then energizes the ultrasonic weld guns and the spring cartridges provide the work required to pierce the laminates. Then the weld guns are de-energized and the diagonal cords are positioned and tensioned for welding. The control unit then commands the power input unit to weld position with the motion being absorbed by the spring cartridge. The weld guns are again energized and the spring cartridges provide the force required for an optimum weld. The controller then commands the weld guns to the retracted position.

4.2.1.6 Preliminary Equipment List — During the course of the predesign task a preliminary equipment list was prepared. This list is given in Table 4-1.

4.2.2 BEAM ASSEMBLY - Of primary concern in beam assembly are the joining methods, joint design, alignment, and machine initial preparation.

4.2.2.1 Ultrasonic Welding — When two faying surfaces of certain meltable materials are vibrated at ultrasonic frequency the inter-surface frictional heat generated can, when properly controlled, cause the surfaces to fuse in the area of applied energy. This method is used for the spot welding of cross members to caps.

In the operation of the ultrasonic welding equipment, a power supply converts 28 VDC power into 20 KHz electrical energy. This high frequency electrical energy is fed to a converter (transducer) where it is changed into mechanical vibrations. The heart of the converter is a lead zirconate titanate electrostrictive element which when subjected to an alternating voltage, expands and contracts with a typical amplitude of 0.02 mm (.00075 inches.) The electrostrictive converter vibrates in a longitudinal direction and couples this motion to a horn, which by design, amplifies and transmits this vibrational energy to the part to be welded. The part to be welded is securely held in some type of holding fixture which is firmly coupled to the mechanically active components of the machine. The holding fixture is analogous to the stationary base of an adjustable "C" clamp. The adjustable movable section of the clamp is similar to the moving, clamping action of the converter/horn assembly.

The welding horn must be tuned to focus, amplify and transmit the 20 Hz mechanical vibrations to a specific point. It is sometimes impossible to design the correct amplitude into the horn initially. This may be because of its required shape, and the nature of the work to be performed. By using various boosters (metal tuned masses), and varying the ratio of the masses on either side of a neutral nodal zone, various degrees of amplification can be obtained. The amplification ratios of boosters usually

Item	No. Req.	Description
1	6	Welder supply, 300 W
2	6	Welder, ultrasonic
3	6	DC motor, brushless, welder drive
4	1	Weld-system interface package: (1) DC-DC converter, 28 V-to-5V/12V (6) Motor control logic/switcher (6) Welder activate/timer logic/driver (1) Input control bus buffer
5	3	Heater interface/switching package - Cap/Crossmember (1) DC-DC converter, 28V-to-5V/12V (23) Power switch (relay/solid state), 10A @ 32V (1) Input control bus buffer (1) Interface/hold logic (23) Switch Driver
6	18	Heater strip - cap, heating section
7	27	Heater strip - cap, forming section
8	45	Infra-red temperature sensor-cap
9	45	Temperature sensor signal conditioner channel - cap
10	3	DC-DC converter - temp sensor conditioning: 28V-to-5V-cap
11	12	Heater strip - cross member, heating section
12	12	Heater strip - cross member, forming section
13	24	Infra-red temperature sensor - cross member
14	24	Temperature sensor signal conditioner channel - cross member
15	1	Data multiplexer, low-level, temperature sensors, 69 channels min.
16	2	Platen actuator interface/switching package: (1) DC-DC converter, 28V-to-5V/12V (3) Power switch (relay/solid state), 10A @ 32V (1) Input control bus buffer (1) Interface/hold logic
17	1	Data multiplexer pkg: 27 hi-level channels, 69 low-level channels, 40 bi-level channels
18	1	Processor: TBD
19	6	Welder position sensors
20	4	DC motor, brushless, material drive
21	4	Material drive, motor controller/interface (1) Commutator circuit (1) Interface/hold logic (1) Input control bus buffer
22	4	Travel sensor
23	4	Travel sensor signal conditioning channel
24	6	Shear controller/interfacer
25	3	Cross member positioner controller (1) DC-DC converter, 28V-to 5V/12V (1) Interface/hold logic (1) Input control bus buffer
26	6	End-of-material sensor

Table 4-1. Preliminary Equipment List

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vary from 1:0.4 to 1:2.5. The lower amplitudes have a greater force capability. It is important to state that each horn/booster combination must be tailored to the specific application for optimum performance. This is because "stalling" of the mechanical energy can happen if the amplitude is not correct for the specific application.

A typical contact pressure of 1.4 MN/m^2 (200 psi) with a weld time of 0.8 seconds produces fused polysulfone surfaces on test laminates that exhibit a single shear strength of 20 MN/m^2 (3000 psi). For design purposes a shear strength of 10 MN/m^2 (1500 psi) has been conservatively assumed.

In the welding operation the horn is first brought into contact with the joint under the force exerted by a preset spring cartridge. The power supply is activated for the required weld time and the horn is vibrated causing frictional heat to be generated which melts the thermoplastic. The thermoplastic will now flow, resulting in a spot weld of the selected horn tip configuration. Since the thermoplastic is still fluid at this point, the horn remains in contact with the material for a selected period of time in a non-vibrating condition to hold the material secure while it is cooling.

The ultrasonic spot weld method is the most attractive joining system investigated for our beam-building system. It is rapid, uses a minimum amount of energy, can be designed in an acceptable size and weight package and produces excellent welds using a variety of weld tips. The type of tips and supporting mechanical and electrical combinations are numerous and varied. Figure 4-8 illustrates several possible weld configurations. The selection of any weld configuration should be based on design requirements and energy limitations.

4.2.2.2 Weld Joints — The preliminarily selected weld joint for beam assembly is shown in Figure 4-9. Each welder is sequentially operated and draws power from

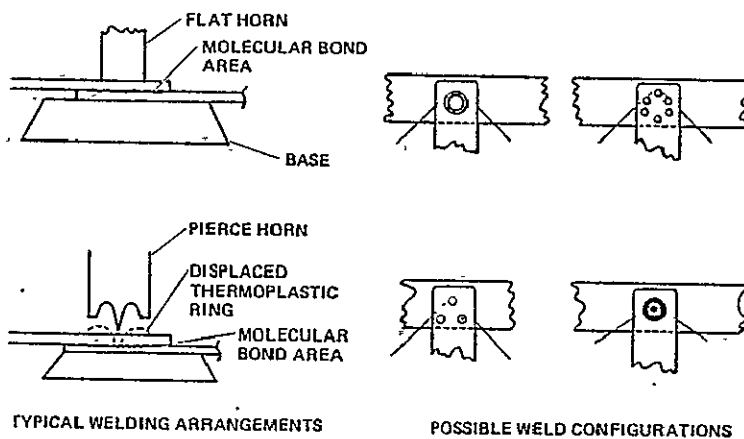


Figure 4-8. Ultrasonic Assembly Welding

from an independent power source. There is a total of 6 welders, two at each cap section. Each welder has a tuned welding horn containing 3 tips. Each tip makes a flat or dimpled spotweld between the cross member and cap section. Cord diagonals which are made of polysulfone impregnated S-glass roving are threaded around the ultrasonic welder pin after holes have been pierced in the members and before

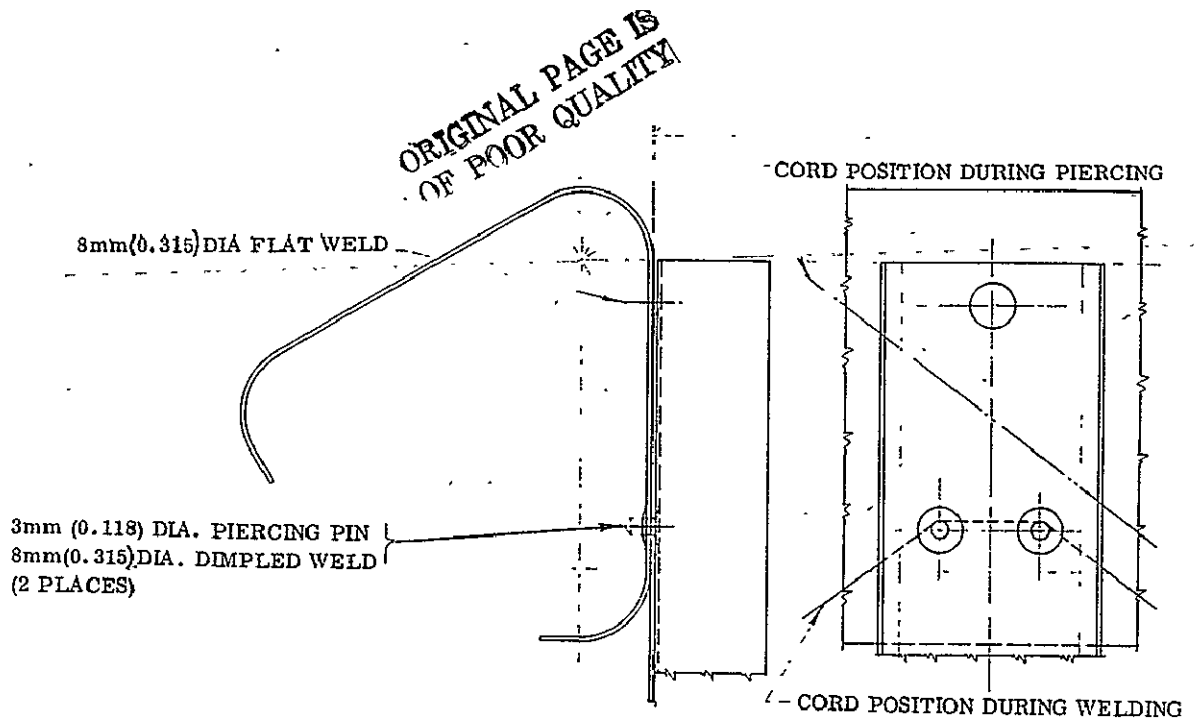


Figure 4-9. Cap/Cross Member/Diagonal Cord Welded Joint.

the final welding action is taken.

4.2.2.3 Alignment — The beam flight test program discussed in Section 3.2.2.1 suggests the use of a laser transit displacement measuring system to provide beam deflection data. The laser transmits track X-Y plane movement of the three targets mounted at the beam's outboard end. Computer processing is used to remove oscillatory displacements. A system of this complexity could be used with the ground operation machine but probably is not warranted. Because the ground system is accessible and visible, simple manned optical observations of pre-attached target boards will provide adequate data.

The collimated nature of cap section laminate material coupled with selective softening of the bend areas indicates that cap section fabrication will run true. Synchronized drive of the three caps assures first order straightness of the assembly. The drive shaft to each cap drive station contains a differential gear and housing. If it proves necessary to have active differential control of cap feed to achieve beam straightness, the addition of a stepping motor drive to the differential gear of two of the drive shafts can be effected. Under control of the system microprocessor, vernier adjustment of feed rates can be continuously made.

Design of the diagonal cord laying mechanism is such as to cancel out the effects of residual differential diagonal cord tensioning bay by bay. For this reason, active twist control by differential cord tensioning is not initially proposed for the ground operations machine. Provisions for this are designed into the cord tensioning device however. Addition of microprocessor controlled solenoid actuators to change the

tensioning spring cartridge fulcrum point can readily be undertaken.

4.2.2.4 Assembly Preparation Cycle — The pre-operational preparation cycle includes those activities necessary to prepare the beam builder for automatic beam production. This involves the insertion of a leader element into the builder cap and channel rolltrusion sections, manual attachment of a cross member (channel) and cord ends, initial tensioning of cord material, drawing of the leader and graphite-thermoplastic (GTP) materials through the builder, and separation of the net leader structure. This cycling is illustrated by Figure 4-10 which identifies 10 sequential steps; these steps are briefly described in the following paragraphs.

Sequence Steps:

1. Leader elements are drawn into all cap and channel sections of the beam builder prior to activation of any system elements. These leaders are spliced to the respective beam elements flat strip GTP materials.
2. Three pre-formed GTP channels are manually bonded to the leader caps, with the cord material placed between the respective cap-to-channel surfaces. This provides a tie-down for tensioning the cords, and provides a semi-rigid structure for following "prep cycle" activities.

The system is now activated, and the cord carriers cycled to tension the cords and to position them for use with next-up channels. This and remaining steps are carried out automatically by the beam builder as a pre-flight operational check.

3. Channel heaters are activated, and the channel materials in the heating section are brought up to forming temperature. The channel materials are drawn sequentially through the heating, forming, and cooling sections by the beam builder channel drive motor. The respective channel leaders, after having been drawn completely into the channel assembly section, are sheared off. The machine is ready to produce usable GTP channels.
4. The channel materials are driven a one element length into beam builder channel turntable guide shoes. These channel lengths are sheared off, held in the grip of the guide shoes.
5. The channel turntables' lift, shift, and rotation sequence is carried out, placing the sheared channels into position over the positioned cords and the leader caps. The weld heads pierce the channels and leader caps, bracing the channels in place over the cords and caps. The channel turntable is rotated back into a "receive" position, slipping the guide shoes from the channels as it goes.

CAP MACHINE SECTIONS

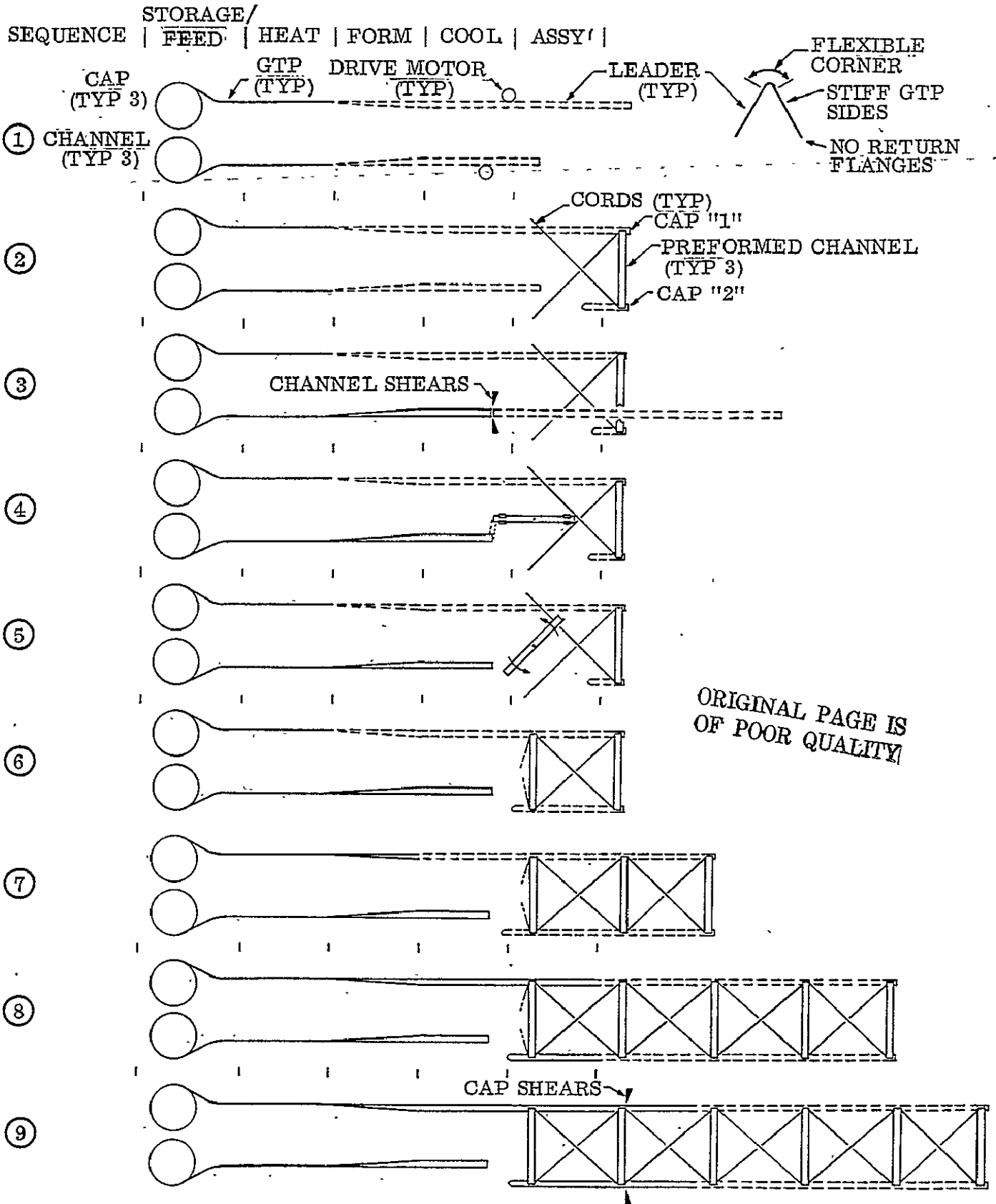


Figure 4-10. Preparation Operation Sequence

6. The cords are tensioned over and around the weld head piercing pins, going into position for the next channel. Final bonding welds are made, tying the channel/cord/cap combinations together; the welders are retracted.
7. Cap heaters are activated, and the cap materials are brought up to forming temperature. Both cap and channel materials are moved one respective element length, and the new channels are sheared off, held in the grip of the guide shoes. Steps 5 and 6 are repeated.
8. The movement and bonding sequence of step 7 is repeated -- twice.
9. Both cap and channel materials are moved one respective element length, and the new channels are sheared off, held in the grip of the guide shoes. Steps 5 and 6 are repeated. The cap shears are now activated, shearing off the leader element structure from what will be the production beam.

From this point on production beams may be built by a repeated series of one element length draws of cap and channel materials, followed by repeats of steps 5 and 6.

4.2.3 FABRICATOR DETAILS. Three areas of predesign detail were accorded special attention because of the key functions involved. These were the design of radiant heating elements, the sensing of material temperature in the heated zones, and the sensing of material travel through the rolltrusion units.

4.2.3.1 Radiant Heating Elements -- Commercial sheathed cartridge heaters were reviewed as radiative-transfer heat sources for use in conjunction with parabolic reflectors sized appropriately for the various-sized material areas requiring heating. The problems which were found forced the conclusion that another approach must be utilized. One such approach, developed herein, uses a bare oxidized nickel-chrome wire wound about a supporting helically grooved base-mandrel.

Some of the cartridge heater application problems which were found are summarized here. Other approaches were developed using bare-wire nickel-chrome: single-wire straight length wire heater, 4-times helically-wound heater, 3-times helically-wound heater (which is recommended). These developments were based on the highest-power requirement area, that of the cap-section center strip.

Cartridge Heater Problems -- Basically, cartridge heaters are defined for high voltage (110 VAC and above) source levels. In this way, comparatively low current densities for given power levels are necessary; thus, relatively small element resistance wires may be used. Shuttle, 28 volts d.c. source excitation has been

ground-ruled for heater use; such usage requires an increased current level, which for given cartridge heater power levels, requires increased element resistance wire sizes to maintain limited levels of current densities. Thus, net larger-sized cartridge heaters result for a given application at 28 volt d. c. excitation.

Sufficient space is not available in the required parabolic reflector envelopes to accommodate the cartridge heater sizes which become necessary.

Another problem area lies in the radiative-transfer application of the beam builder versus the normal form of application of cartridge heaters. Vendor defined power and surface temperature limits are based on conductive heat transfer, with tight-fit intimate and precision surface contact with the medium (normally a solid material) to be heated. Significant parametric data for in-vacuum non-contact applications is not available from the vendors contacted.

Nickel-Chrome Resistance Wire — The most stable nickel-chrome alloy used for resistance heating is that of 80%, 20% composition. Two resistivity figures exist for this alloy, differing with regards to relative trace levels of iron in the alloy:

1. 107.9×10^{-6} ohm-cm;
2. 112.2×10^{-6} ohm-cm.

The second of these values is used herein, based on correlation with one vendor's* specifications on various AWG wire ohms per foot.

Certain factors of uncertainty exist with regard to the emittance values used within this report. A figure of 0.20 is available for non-oxidized nickel-chrome (80%, 20%) alloy, and parameters in the region of 0.80 have been determined and reported ** for the alloy, oxidized for 15 minutes at a temperature of 1400K (actually, the published emittance figures are closer to 0.86 at the temperature levels found herein, but this analysis will tend toward a conservative approach since actual surface conditions are such a factor with regard to this parameter). Emittance is significant herein with regard to definition of the stable operating temperature level of the nickel-chrome element wire.

Basic Functions — Certain functions are common to this analysis, as are some assumptions made to define a worst-case condition. The d. c. excitation level delivered to the heaters is taken as 27 volts; this is obtained on the assumption of

* Consolidated Wire, Chicago, Illinois.

** "Thermal Radiative Properties - Plenum Press Handbooks of High Temperature Materials," Wood, Deem, and Lucks; Pg. 114, for low temperatures, as rolled material (non-oxidized).

of a 0.5 volt drop across the excitation distribution lines, with Shuttle source excitation at its minimum of 27.5 volts.

Whether or not the wires defined for the heaters in the analyses can support the required power levels is verified or denied by determining the actual stabilization temperature of the wire in vacuum, via application at the Stefan-Boltzmann radiation equation:

$$\begin{aligned} P_r &= \text{total radiated power per unit radiant area,} \\ &= \epsilon \sigma T^4 \quad (\text{watts/cm}^2), \end{aligned}$$

where: ϵ = material emittance,

$$\begin{aligned} \sigma &= \text{Stefan-Boltzmann constant} \\ &= 5.673 \times 10^{-12} \text{ watts cm}^{-2} \text{ }^\circ\text{K}^{-1}, \end{aligned}$$

T = material temperature ($^\circ\text{K}$).

Required power levels from the heaters are obtained from analytical figures for the power required to heat the graphite thermo-plastic (GTP) material from 255K (0°F) to 490K (425°F) in 40 seconds, over the required overall length of material. An additional 6% loss figure is applied to this figure to account for reflector losses.

Heater Design

The beam builder cap heater section involves an overall effective length of 1.47 meters. For this development the heater is considered as made up of two separately controllable segments over the effective length; this is in satisfaction of presently established thermal operating start-up requirements.

One approach to the heater configuration is that shown in Figure 4-11 wherein a single-length nickel-chrome element (of diameter TBD, but no greater than 1/8 inch) connects to excitation voltage at three points. This structure involves the making of suitable electrical-lead bonds to the heater element, one at each end for positive-excitation interfacing, and one at center for excitation return interface.

Requirements applicable to the system cap heater section of the beam builder are:

$$\text{Heater power, center strip} = 188.3/.94 \quad 200 \text{ watts.}$$

$$\text{Heater power, edge strips} = 137.7/.94 \quad 147 \text{ watts.}$$

A. Straight-Line Element

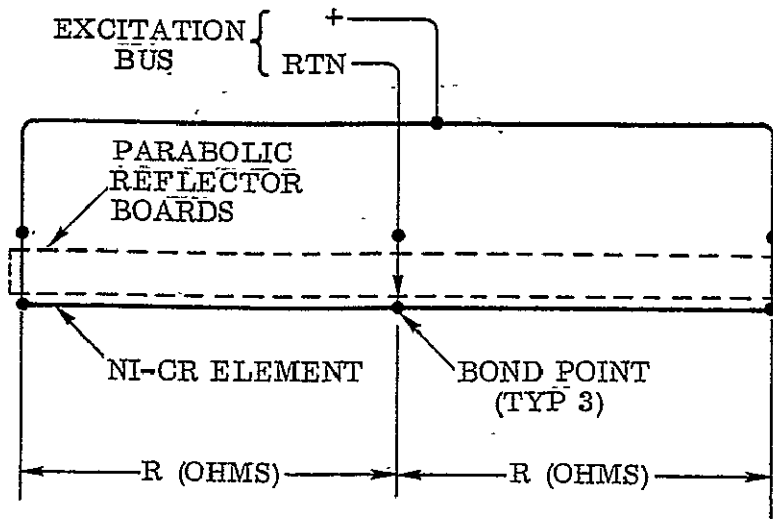


Figure 4-11. Single-Element Heater Structure

Consider the center strip requirements. Since each half of the heater element can be independently excited by the available excitation voltage, the required 200 watts of power is made up of the sum of the two separate segments. Calculations yield a total overall heater element resistance of 14.58 ohms. This value, and the resistivity figure of 112.2×10^{-6} ohm-cm, yield a necessary minimum cross-sectional element

wire area of 0.113 mm^2 . The nearest (no less than) standard AWG nickel-chrome wire-size to this is 26 AWG, of cross-sectional area 0.1288 mm^2 , diameter 0.4049 mm, and resistance-per-foot 2.670 ohms.

With this 26 AWG wire, then, the actual power produced at 27 volts is 226.45 watts. The total run (147 cm) wire surface area, for radiation emission, is 18.70 cm^2 . Therefore, the net power per unit area radiated is 12.11 w/cm^2 . Applying this figure to the Stefan-Boltzmann radiation equation, using the oxidized alloy emittance value of 0.80, we obtain a wire temperature of 1278 K (1841°F). At this 1841°F temperature a visible lemon-yellow emission may be apparent from the heater element wire.

The melting point temperature of the nickel-chrome alloy is 1673 K (2552°F). A higher operating temperature level than the above is probable, since the excitation source voltage can be at a level as high as 32.5 volts d.c. Thus, a worst-case temperature level can be defined by assuming the application of the 32.5 volts to the heater. This gives a wire temperature of 1402 K (2064°F).

Therefore, operating temperatures, in themselves, do not pose a serious problem from the power-in;power-out standpoint. They do pose a problem, however, from another standpoint, involving thermal expansion of the heater element material. Over the temperature difference involved a length change of about 2.6 cm occurs in the element.

This lengthening must evidence itself as some net overall distortion of the element wire, assuming solid end support; most likely this will appear as

random movement away from the focus point of the parabolic reflector. Some idea of the degree of this effect can be gained by considering a simple case of an equivalent line supported at each end only, defining the displacement as on a circular radius.

A series of iterative calculations yields the maximum displacement of the element wire from its "cool" position as approximately 12 cm. This displacement, obtained for the 27 volts level of excitation, is indicative of the problem which is present: a displacement in this situation and configuration could be more than enough to move the hot, conducting, element wire into contact with either the parabolic reflector or the GTP material.

Even with multiple supports acting to limit independent displacements of the discrete sections of the element wire, these displacements will still be such as to make this approach indeterminate, at best.

B. Coiled Elements

Because of the problems determined in the preceding section for a straight-line element heater, coiled-element heaters were investigated.

To do this for a helically-wound element, it was first necessary to define a net wire-length of heater element for consideration. Doing this, the next steps required involved development of operating temperature levels, definition of physical helix parameters, and definition of a nominal helix base diameter. With these functions determined and defining operational limits, nominal dimensions could then be chosen, and the net effect of their choice on heating parameters could be determined.

The detailed calculations showed that a wound heating element is feasible and applicable. What must yet be determined is the material which, both electrically and thermally non-conductive, can be formed or shaped to the established requirements. Figure 4-12 illustrates these requirements, and also shows the relative arrangement/scale of the nickel-chrome wire lay. This basic design was found applicable to each of the strip heating applications.

Other items which remain to be considered relate to techniques of electrical and mechanical termination to the heater, and an analysis of the effects of thermal conduction between the two defined segments of the heater with one segment "on" and the other "off". It may be concluded a better arrangement is obtained, in these references, with physically separate segments.

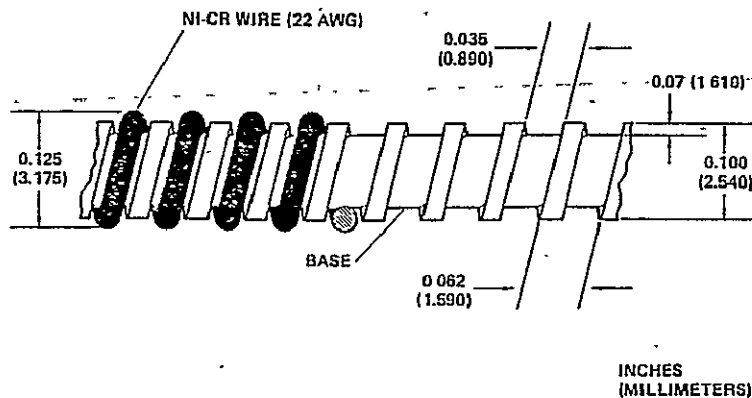


Figure 4-12. Heater Element Detail

4.2.3.2. Material Temperature Sensing —

The range of material temperatures necessary for satisfactory beam builder forming of the GTP laminate gives radiated emissions from that material in the infrared spectral band of 5 to 8 microns. Of the two generally applicable categories of infrared detectors (photon and thermal), the photon type is not sensitive to this spectral band except when super-cooled to levels of 77°K and lower; such supercooling is considered

to be impractical in application, and thus photon detectors are not considered further.

In the thermal category, detector types which are sensitive to the 5 to 8-micron band are (1) pneumatic (Golay), (2) thermocouple, (3) thermistor (bolometer), and (4) thermopile. The thermopile, as primary, and the thermistor, as secondary, types are most appropriate to the beam builder for the reasons outlined in the following paragraphs.

The pneumatic thermal detector is based on a gaseous expansion with heating, with a resultant coupled mechanical motion acting as an indicator. This type is highly efficient, but extreme fragility makes it impracticable.

The thermocouple thermal detector is a single-junction device, constructed of a fine wire (diameters in the 25 micron region) junction which is fastened directly to an infrared absorbent blackened receiver area. As for the pneumatic detector, fragility makes the thermocouple detector impracticable.

The thermistor bolometer detector is based on a change in material electrical resistance with heating (on the order of 4% per °K). Consisting of thin flakes, formed by sintering a mixture of metallic oxides, mounted on an electrically insulating substrate which is, in turn, mounted on a metallic heat sink, the thermistor bolometer detector is relatively rugged and requires no special cooling for good sensitivity. These factors, and others, make the thermistor bolometer detector a candidate for beam builder use.

The thermopile detector consists of a number of thermocouples connected in series. The thermocouples involved here are not the same type as discussed above; in this case they consist of evaporated overlapping thin-film materials formed on a thermally insulated layer set in the middle of an aluminum (typically) heat sink. Reference

junctions are formed where the evaporated films contact the heat sink. With this structural configuration the thermopile detector, like the thermistor detector, is relatively rugged and requires no special cooling for good sensitivity, making it a candidate for beam builder use.

The thermistor and thermopile detector types are comparable in terms of response parameters (detectivity, time constants, wavelength range), can be used in DC configurations (mechanical radiation chopping not necessary), and are available in simple packages. Each requires information relative to ambient temperature level for accurate (temperature) evaluation of output signals.

The thermistor detector type is typically used in divider or bridge configurations, thereby mandating the presence of a stable reference bias voltage. With the presence of biasing, the additional effects of self-heating due to bias currents and resistance changes must be contended with. The relatively high-impedance device levels require the use of comparatively high impedance amplifier electronics.

As opposed to the thermistor detector, the thermopile detector is a self-generating-signal device, thereby not requiring biasing excitation nor facing the problems of self-heating. Finally, the thermopile detector is a relatively low-impedance device, which reduces impedance requirements on amplifier electronics.

The above summary of device-types leads to recommendation of the thermopile detector as the sensor to be used for infrared non-contact temperature measurement on the beam builder.

Sensor Packaging/Installation

A sensor package available from several thermopile detector manufacturers is that of a transistor standard TO-5 case, as represented in the cutaway view of Figure 4-13. The sensing junction thin-film region is covered with an infrared blacking, improving radiant energy absorption into the junction. The reference junction thin-film region is in contact, via an electrically-isolating film, with the heat sink, providing a reference temperature point; this point will be relatively stable assuming a good thermal bond exists between the TO-5 can header and the mounting surface. The can aperture provides the entry point for infrared radiation, and controls the detector field of view by its diameter. The window acts as a seal, can act as a bandpass (spectral) filter, and can act as a radiant attenuator; the latter two functions are determined by the window material.

An exploded view of elements for installing these sensors in the respective beam builder heating sections is given in Figure 4-14. The threaded compression insert provides a tight compression bond between the TO-5 can header and the thermal-

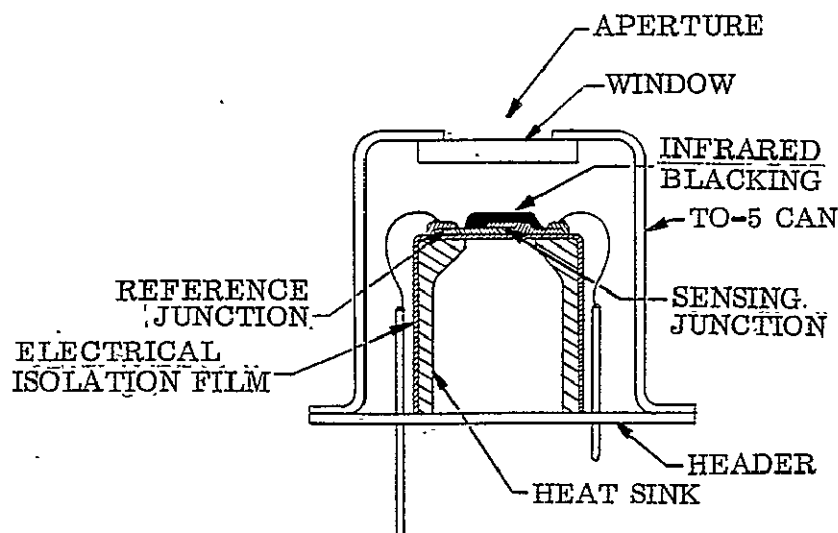


Figure 4-13. Section View-Thermopile Detector TO-5 Package

conductive sensor mount. The structure-mate sensor support provides the thermal interface between the sensor mount and the beam builder structure. Finally, the socket support locks the socket in position while connected to the sensor's leads.

Figure 4-15 illustrates a typical installation of the sensors in the cap heating sections. The coolant lines shown in the structures establish the stability of the reference junction of the

thermopile via the heat-sink-to-header-to-mounts interface.

Parametrics

Specific parametric information, regarding input-to-output signal levels (source infrared watts/cm² versus detector generated voltage) and their relation to source-material temperatures, awaits definition and the results of experimental and

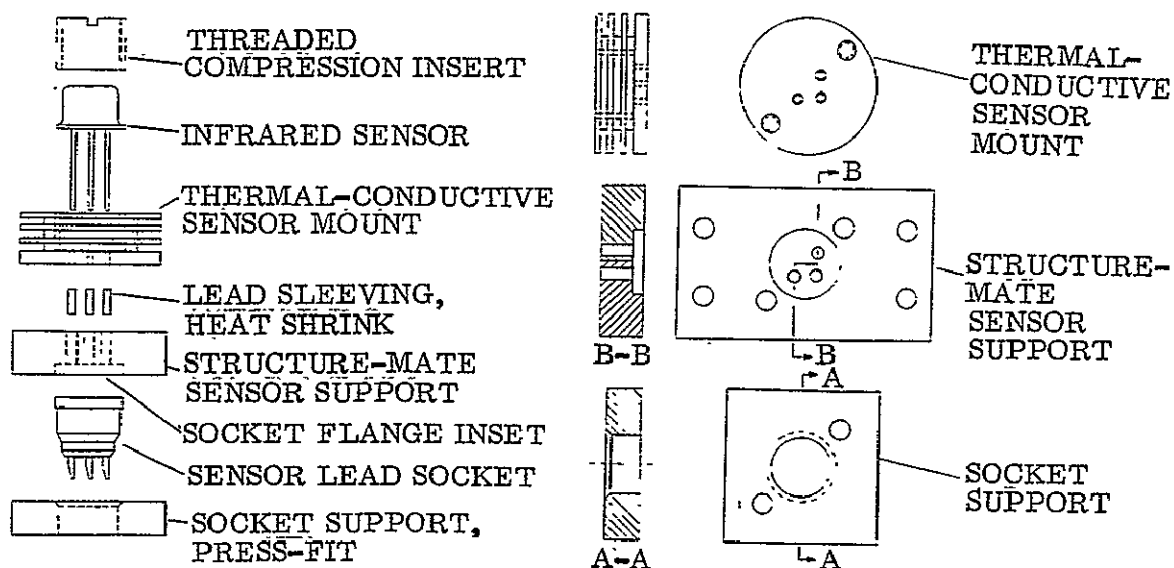


Figure 4-14. Temperature Sensor Mount Assembly Elements

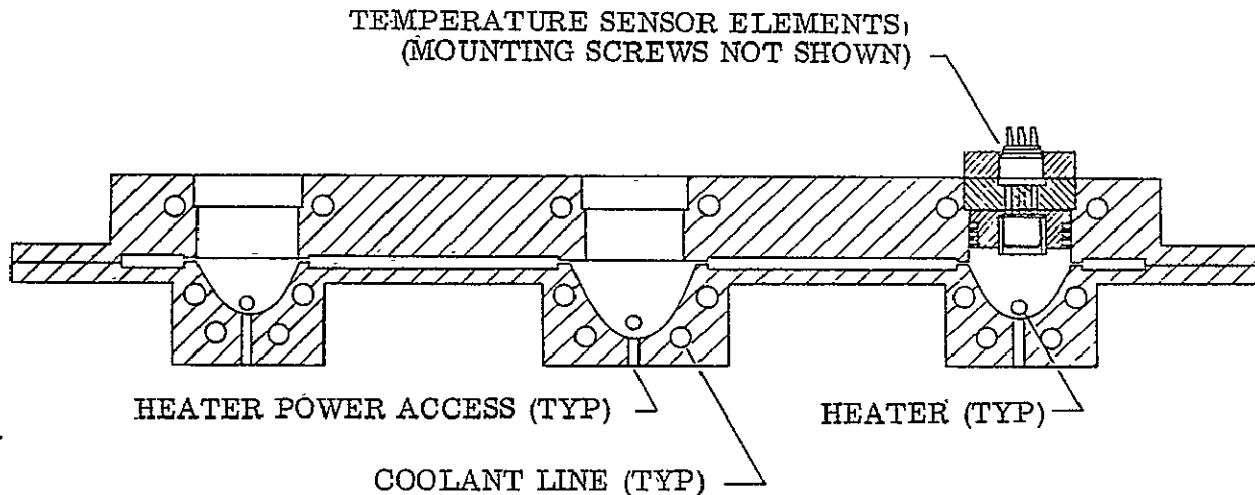


Figure 4-15. Temperature Sensor Installation - Cap Heating Section

analytical work on specific sensors and on the various installation configurations involved in the beam builder. Further work is needed in these areas, including analysis of source-to-sensor configuration effects (i.e., of reflections, field-of-view), specific sensor analyses and testing, and net effects of varied ambient levels on sensor operation.

4.2.3.3 Material Travel Sensing — One motor installation is used on the beam builder for synchronized cap material drive (all three caps), and three motors for individual cross-member material drive. Material drive forces are produced via gearing down from the motor speed to the necessary drive roller speed, thereby obtaining the necessary drive torque from the low-torque drive motor.

Using the net drive ratios, material travel distance can be calibrated to the net angular rotation of the drive motor. In turn, this angular rotation can be metered by coupling a rotary pulse generator to the drive motor shaft and counting up the number of resultant output pulses produced from a start point. Thus, the required material travel distance can be related to a specific pulse count figure.

Proposed implementation of this function is to provide a peripheral unit countdown register for each drive motor. Each register will be loaded with a preselected distance count by the system controller processor. The processor will enable the peripheral units upon motor startup, and the register contents will be counted down to a zero value, using rotary generator pulses as the countdown clock, at which point the motor will be commanded, by the processor, to stop. Peripheral unit counter status can be given to the processor by peripheral-produced interrupts.

A gradual stop, which can minimize possible material drive overshoot, can be developed by operating with a series of "graded" interrupts, again produced by the

peripheral units, which activate processor "slow down" commands to the drive motors.

A representative rotary pulse generator is the Veeder-Root series 1848, which is available with resolutions up to 600 pulses per shaft revolution. Other device parameters are: (1) 0 to +4 volts square wave output, (2) operation up to 3600 rpm continuous, and (3) operating temperatures from 244K(-20F) to 338K(150F). This unit requires 6 volts dc excitation at 300 mA maximum.

An idea of the resolution possible with this approach can be obtained by assuming a conservative gear-down ratio of 50:1 in conjunction with a 50 mm drive gear. Such a gear yields a gear travel of 157 mm per drive gear revolution; using the gear-down ratio, this produces an equivalent material movement of 3.14 mm per drive gear revolution. Using a 600 pulse per shaft revolution rotary pulse generator then yields a net material motion resolution of 0.005 mm per pulse count.

4.2.4 COMMAND AND CONTROL. The fabrication machine functions are controlled automatically by a preprogrammed microprocessor. Operator initiation, program selection and override is provided.

4.2.4.1 Control Software Definition — Figure 4-16 outlines the functional areas of coverage of the beam builder system controller. As illustrated, there are three major control software modules, applied through a central control block to three beam builder subassembly fabrication functions. These control modules, broken down in further functional detail in Figure 4-17 are:

- | | |
|--------------------|---|
| 1. Pre-load | Enters and coordinates those parameters/functions leading to proper performance of the pre-load function of the beam builder, effectively priming the builder for operation in a shuttle bay. |
| 2. Production | Enters and coordinates those parameters/functions leading to proper performance of the production function of the beam builder, resulting in the creation of a full-scale beam assembly. |
| 3. Command/Display | Provides for interface coordination with builder-external functions (e.g., with an operator in the shuttle flight deck), acting as a channel for data function formatting and readout, or for manual override commands. |

Each of the control modules has an input/output relationship with all of the sub-assembly fabrication functions. The subassembly fabrication functions are broken down in further functional detail in Figure 4-18.

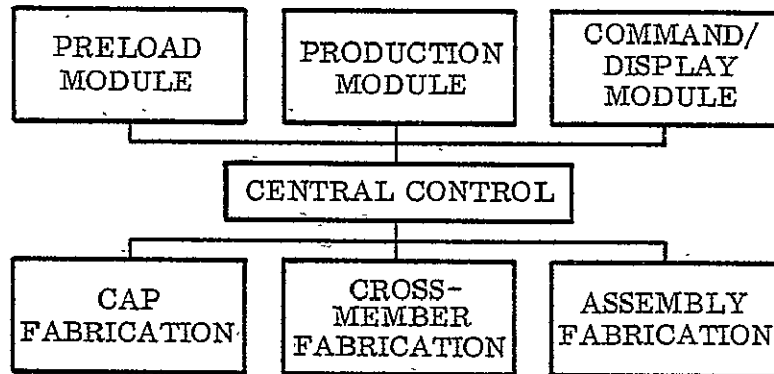


Figure 4-16. Functional areas - beam builder system controller.

Preload Module	Loads preload temperature limit (Hi/Lo) values. Loads preload beam length value. Loads preload bay length value. Initiates system position detectors status review. Presets (corrects) out-of-position elements. Rechecks. Loads preload weld schedules. Commands all heaters to initial off condition (initialization for start). Activates cycle start - - Inhibits cap run, with crossmember run active (initial phase). - Activates cap run (buildup phase). Tracks overall beam length; terminates cycle at required length. Activates beam shear. Shuts down system.
Production Module	Loads production temperature limit (Hi/Lo) values. Loads production beam length value. Loads production bay length value. Initiates system position detectors status review. Presets (corrects) out-of-position elements. Rechecks. Loads production weld schedules. Commands all heaters to initial off condition (initialization for start). Activates cycle start. Tracks overall beam length; terminates cycle at required length. Activates beam shear. Shuts down system.
Command/Display Module	Command - Translates external request(s) for data output. Accepts/transfers manual override commands. Transmission conditioning: serial-to-parallel conversion Display - Formats data: scaling - engineering units conversion - data tagging Transmission conditioning: parallel-to-serial conversion

Figure 4-17. Control modules functional detail.

Cap Fabrication	Heaters — Command power switches on/off, individually and mixed. Temperature Sensors: Data multiplex sample command, by set Reference (ambient) temperatures evaluate Material temperatures evaluate Limit checks (Hi/Lo) evaluate Material Drive — Drive motor power control (on/intermediate/off) Travel Sense: Interrupt response Enable counters interface Preload counters Cooling Platen — Drive control (open/close) Position detect (open sense/close sense)
Crossmember Fabrication	Heaters — Command power switches on/off, individually and mixed. Temperature Sensors: Data multiplex sample command, by set Reference (ambient) temperatures evaluate Material temperatures evaluate Limit checks (Hi/Lo) evaluate Material Drive — Drive motor power control (on/intermediate/off) Travel Sense: Interrupt response Enable counters interface Preload counters Cooling Platen — Drive control (open/close) Position detect (open sense/close sense) Shear — Drive control (open/close) Position detect (open sense)
Assembly Fabrication	Cord Drive — Drive control (up/down) Position detect (full up/full down) Crossmember — Drive control (cw/ccw) Turntable — Position detect (full cw/full ccw) Crossmember entered (full in) Welders — Drive Control: Down - to setup (hold) position Down - to final weld position Up - to fully released position Position Detect: Setup position sense Final weld position sense Fully released position sense Weld Schedules: Setup weld cycle Final weld cycle Welder Excitation: Power control (on/off) Shear — Drive control (open/close) Position detect (open sense) Material Supply — End of material detect Heaters shutdown control override (temperature sensors protect)

Figure 4-18. Subassembly Fabrication Function Detail

The program flow diagram is given in Figure 4-19 showing sequence of events and basic logic of the system. The set-up logic is shown in Figure 4-20 and gives the three steps leading to production initiation. The operator, in the ground-based version, simulates the mission specialist in the shuttle on-orbit experiment.

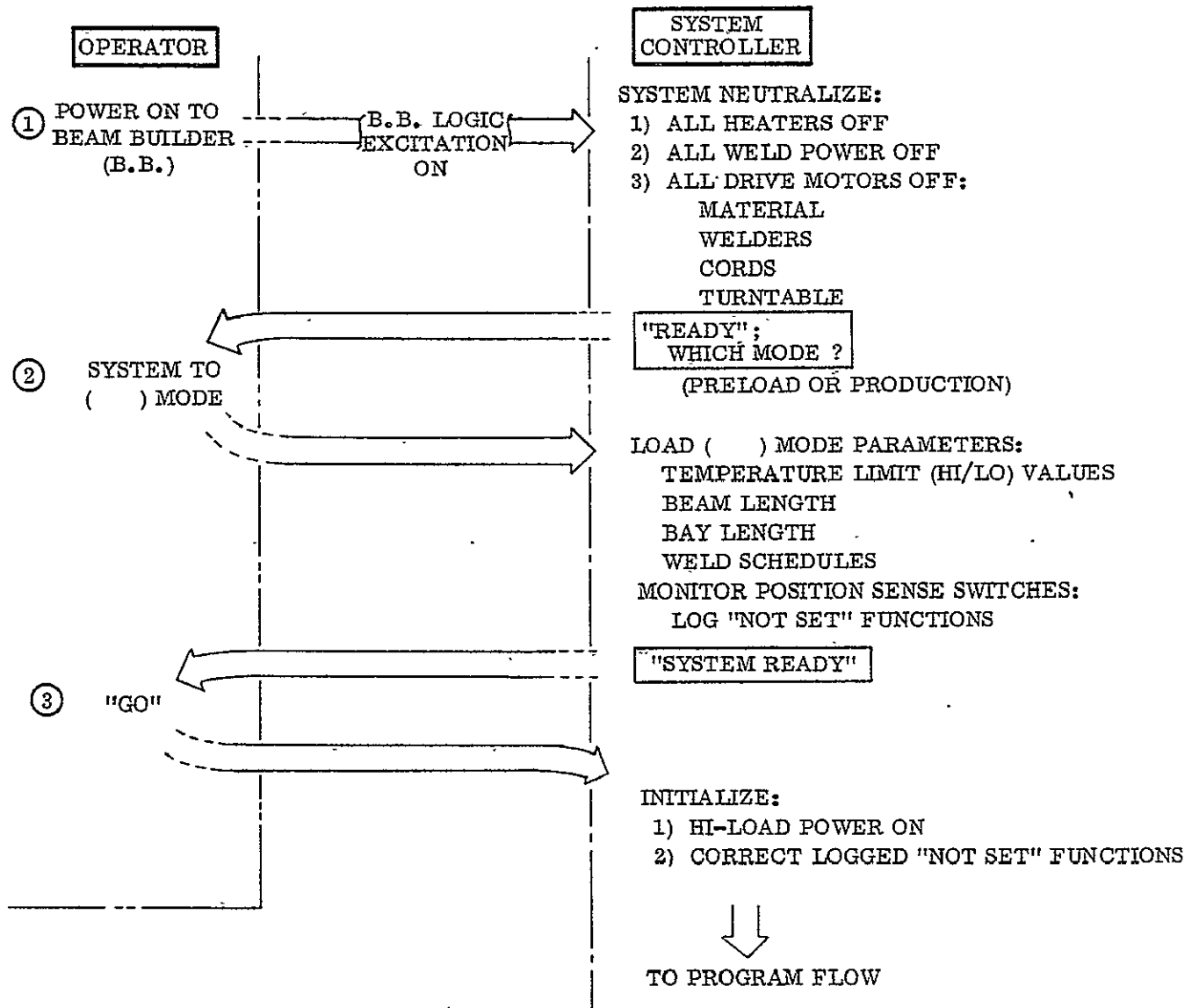


Figure 4-20. Set-up Logic

4.2.4.2 Heater/Sensor Configuration — Each cap heater section of the beam builder will have two separately controllable heater elements per bend joint. Thus, since there are three cap bend joints, each cap heater section will have a total of six heater elements. The same two-per-bend-joint ratio will apply to each cross member heater section, giving four heater elements per cross member heater section. A schematic configuration is shown in Figure 4-21.

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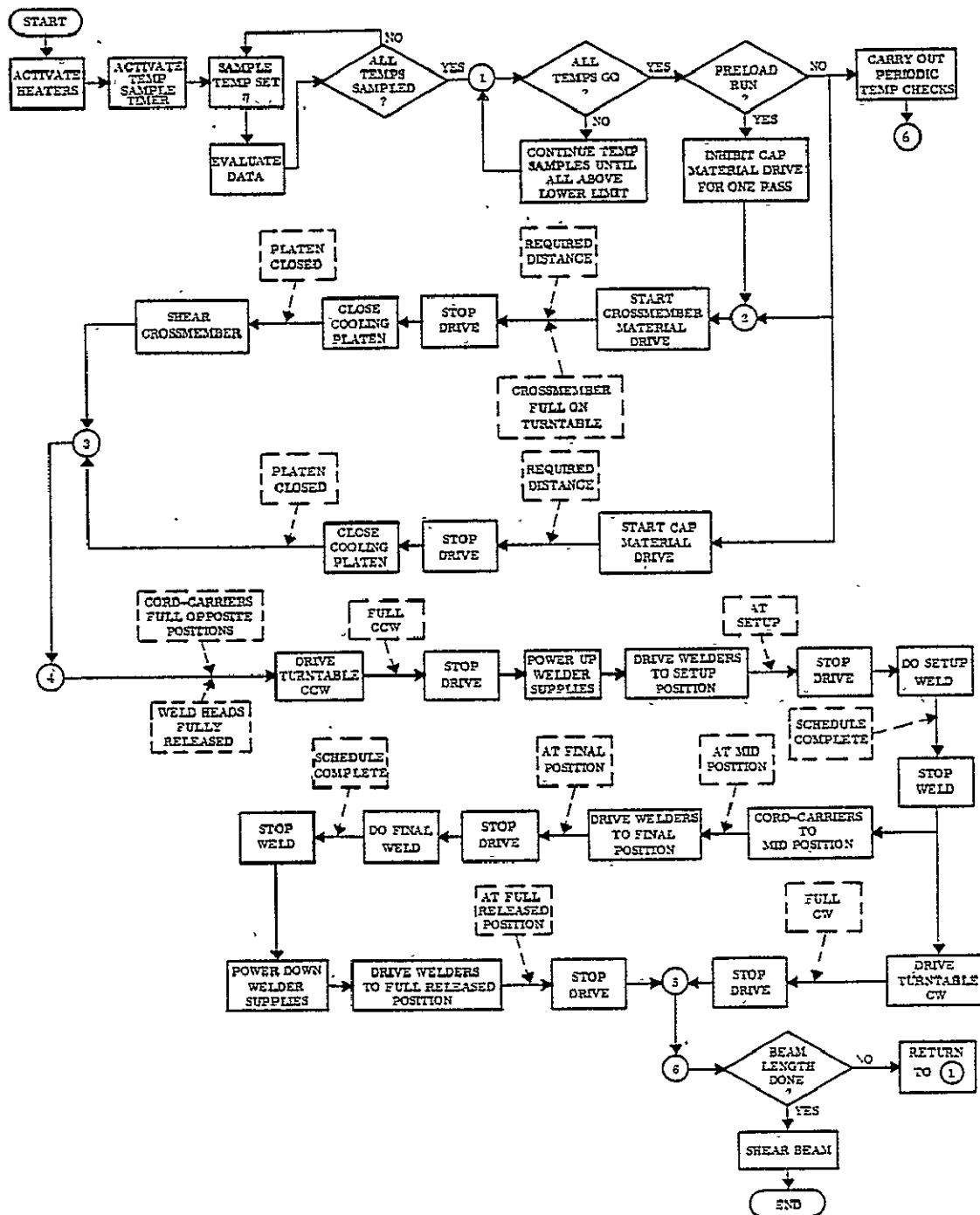


Figure 4-19. Program Flow Diagram

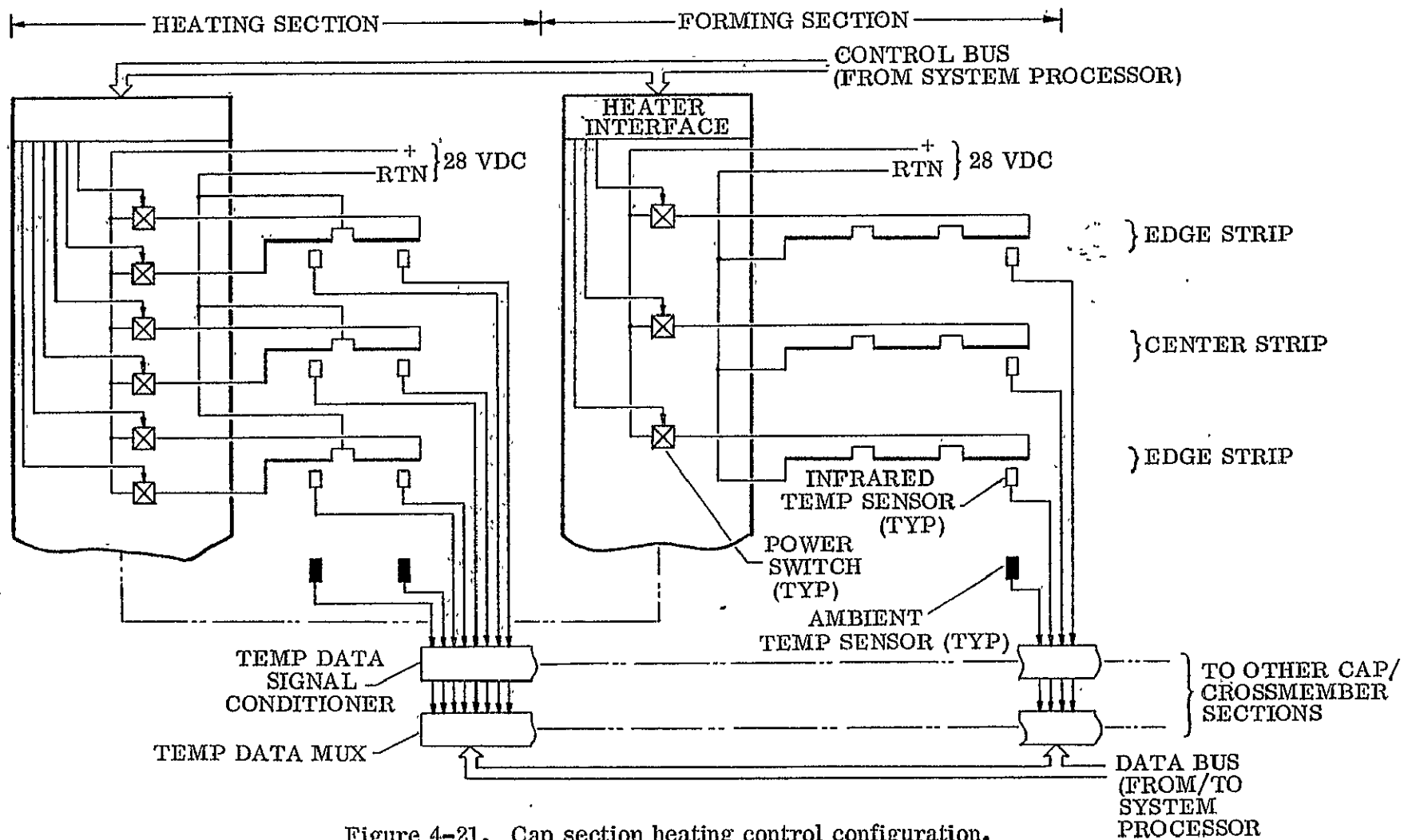


Figure 4-21. Cap section heating control configuration.
(one of three sections shown)

Each cap forming section will have three commonly controllable heater elements per bend joint, for a total of nine heater elements (making up three control sets). Each cross member forming section will have only two commonly controllable heater elements per bend joint, for a total of four heater elements (making up two control sets).

Each heater section (cap and cross member) heater element will be matched by an infrared sensor (monitoring material radiation energy). Sets of these sensors will be matched by sensor-medium ambient temperature monitoring sensors. Each forming section (cap and cross member) heater element control set will be matched by the same configuration of sensors.

The definition of the above paragraphs is illustrated symbolically by Figure 4-22. Coding indicated about the illustration periphery provide for unique identification codes for the respective heaters and sensors. Thus, the first heater/sensor of the first cap section (CAP 1C1) is uniquely identified as C1H11 (this is the left-most upper dot position in Figure 4-22); similarly, the first ambient (A) sensor of this first cap section is uniquely identified as C1H1A.

Groupings outlined by dashed lines in Figure 4-22 are representative of groupings of sensors for data gathering purposes, and of heaters for command control purposes. Thus, as shown in the figure, there are nine heater/sensor sets involved. As an example of this coded structuring, the following sensors' outputs will be sampled at a given time as one data set for system processor evaluation:

C1H11, C1H12, C1H13, C1H14, X1H11, X1H12, X1H1A.

Similarly, the following heaters will be commanded (on or off, as individual circumstances dictate) as a set by the system processor:

C1H11, C1H12, C1H13, X1H11, X1H12.

Finally, each heater and/or sensor set as a whole can be identified as a set by a code made up of the cap/cross member section identifier numeric digit and the heater/forming section alphanumeric identifier. Thus, the preceding sensor and heater sets which were listed as examples are both labeled as the 1H1 sets.

For temperature monitoring/heater control, then, Figure 4-23 illustrates in block diagram form a possible system configuration for the net sensor-interface/heater-control elements. As presented, the processor operates with an address bus to access particular interface units, with a data bus for transfer of command or data words, and with a control bus for linking of control signals such as interrupts.

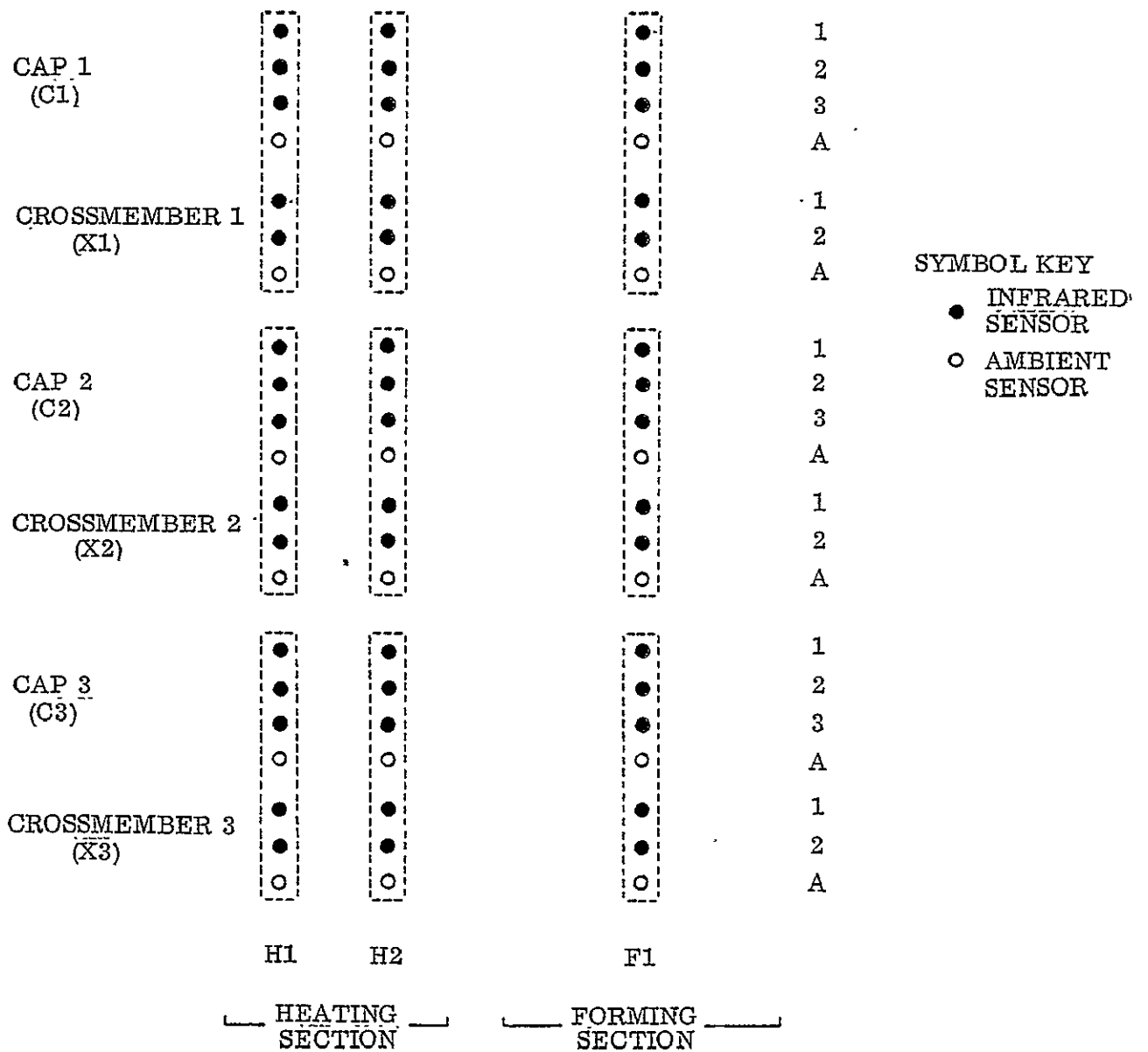


Figure 4-22. Heater/Sensor Control Sets

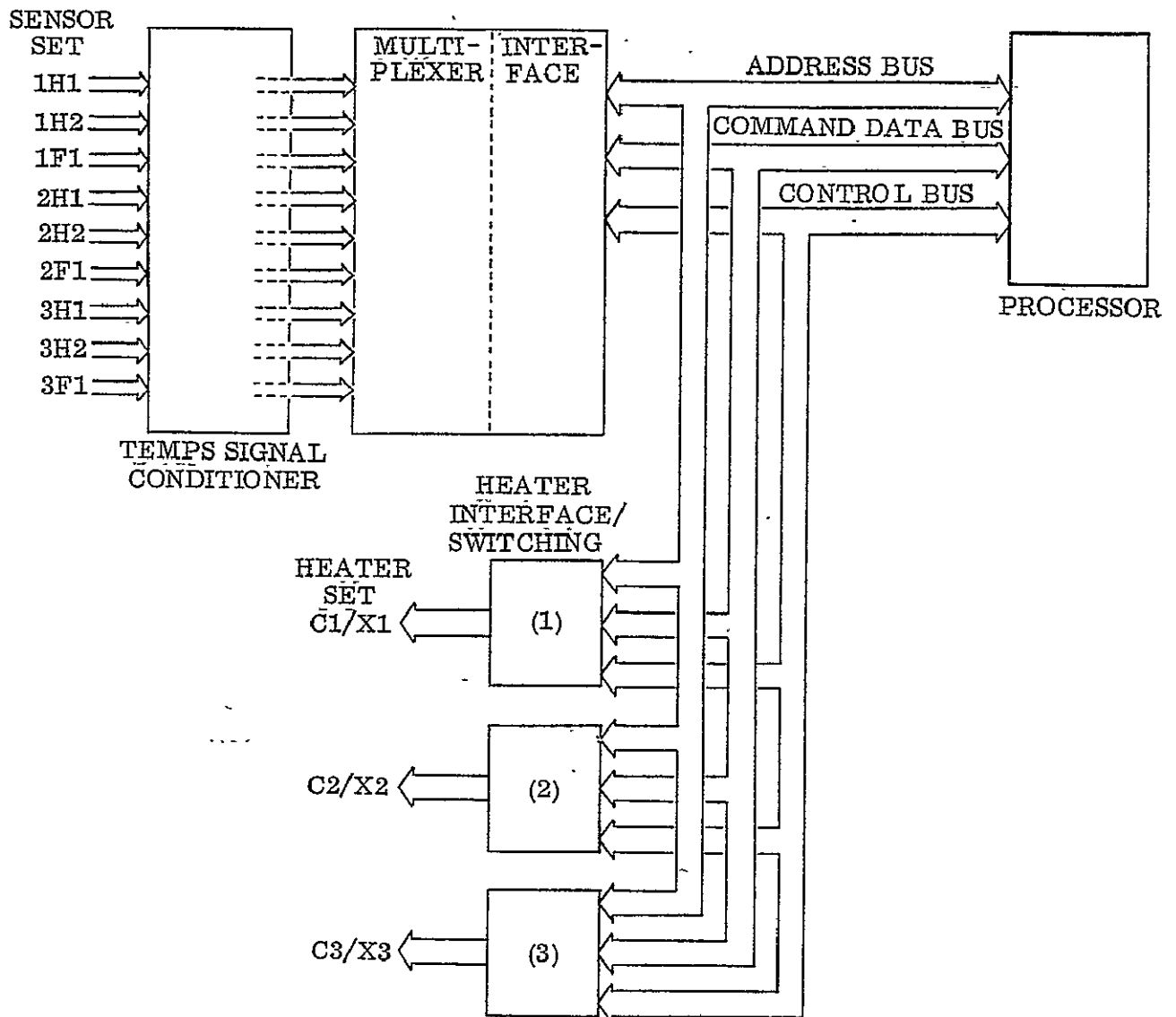


Figure 4-23. System Configuration for Sensor-Interface/Heater Control Elements

As shown, system functional elements consist of three interface/switching packages (one per cap/cross member set), a single temperature sensor signal conditioner package, and a single temperature sensor data multiplexer/interface package.

The heater interface/switching packages provide three functions:

1. Appropriate interface buffering with the processor busses.
2. Command word latching elements for sustained drive of switching elements.

3. High power switching elements for application of shuttle power to beam builder heater elements.

The elements of a processing/command program sequence are given in Table 4-2 which defines the functional operations for a given heater/sensor set.

4.3 APPROACH EVALUATION AND RECOMMENDATION

This preliminary design for a fabrication machine for ground operation is the product of a continuous interactive systematic evaluation of alternative design and operational solutions to the currently known requirements. The approach described above can be evaluated for its relationship and applicability to the eventual flight experiment, and its flexibility for meeting undefined requirements for physical size, power, rate of production, and trouble-free operation in future missions.

4.3.1 ROLLTRUSION UNITS — These units are essentially identical to first generation flight (experiment) equipment. For simplicity and accessibility the heating, forming, and cooling sections are located in line. This results in a slim line layout. Machine width can be traded against length in a couple of ways. The heating section can be located above the forming and cooling sections. In this configuration the storage reel would be mounted forward, and the material run initially in a counterflow direction followed by a 180 degree turn into the forming section. Added complexities are curved heater forms and unnecessary bending of the material in the fully plastic bend zone condition. A second approach is to wrap the heating section around the storage reel periphery. In addition to the added complexities described above, access to and replacement of bulk material will be more difficult. Flexibility to accept these changes is however inherent in the basic concept and available to meet specific future needs.

The heating arrangements were optimized for maximum power usage efficiency and this criterion, for in-space operation seems unlikely to change. The upper limit for heat application rate to GTP strip material has yet to be determined. Applicable factors are available power, heater element design, temperature control (especially over-swing), and material surface characteristics. A fabrication rate of three meters per minute with the present approach is probably attainable by development.

Owing to the essentially zero elongation characteristic of graphite fibers the production of curved cap sections by a rolltrusion unit would appear infeasible. By the same token, fiber collimation assures the inherently automatic production of straight sections. For the fabrication machine to produce curved assembled beams the curvature must be introduced elastically and retained by an internal force/moment distribution utilizing cross member end fixity and differential tensioning of

Table 4-2. Processing/command program sequence — heater/sensor set.

FUNCTIONAL COMMAND	COMMAND DESCRIPTION
1. Start	
2. Access MUX Interface	Address bus: contains interface unit ID word Data bus: contains desired parameter set's ID word Control bus: carries data transfer strobe (strobe loads the set ID word into interface unit register, which then uses ID to select multiplexer channel set for sampling and conversion)
3. Wait	Processor waits for completion of multiplexer cycle (sampling, A/D conversion); assumes a rapid conversion device.
4. Receive MUX Interrupt	Multiplexer interface generates a "data ready" interrupt on control bus; converted data value is present on data bus.
5. Read MUX Data	Processor draws data word into accumulator, and generates a "data received" strobe on control bus back to multiplexer interface. Strobe initiates next (if applicable) multiplexer cycle.
6. Move Data to Storage	Processor transfers data word from accumulator to required memory location.
7. Repeat 6 Times	Steps 3 through 7 repeated until the 7 data values of a complete set have been attained.
8. Calculate Cap Ambient	Processor computes and normalizes cap ambient temperature value.
9. Calculate Crossmember Ambient	Processor computes and normalizes crossmember ambient temperature value.
10. Calculate Cap Temp	Processor computes and normalizes cap temperature value; includes correction with cap ambient value.
11. Compare with Upper Limit	Processor computes temp value with upper limit value UPLIM: a. Less than UPLIM: set heater command word bit to ON b. Greater than or equal to UPLIM: set heater command word bit to OFF
12. Repeat	Steps 10, 11 repeated for remaining cap temps, then for crossmember temperatures; net of five passes.
13. Access Heater Interface	Address bus: contains appropriate heater interface unit ID word Data bus: contains complete 5-bit heater command word generated in preceding, and heater set ID (1 of 3). Control bus: carries data transfer strobe (strobe loads set ID, which steers the data word (command), and the heater command word into heater interface unit).
14. End	

the diagonal cords.

On-orbit maintenance of machinery of this type will be extremely difficult. A primary driver in design has therefore been ruggedness, long life, and modular replaceable units. These features are inherent in the designs presented.

4.3.2 ASSEMBLY UNITS. The mechanism developed for placement and welding of formed cross members is straightforward. In the baseline beam structural concept used for the purposes of this study the cross members run at ninety degrees to the cap members and the beam is cord-braced diagonally. The same assembly mechanism can readily be modified for the placement of cross members at any angle to suit basic beam design. A practical cord dispensing, laying, and tensioning arrangement has been predesigned for beams utilizing cord bracing. A flexibility to accommodate future beam design alternatives is therefore assured.

4.3.3 MACHINE INTEGRATION. Basic support structure of the machine is applicable in arrangement to any triangular cross section beam of equilateral form. It forms a stiff mounting for mechanical units and eventual flight loads during delivery to orbit. It has the flexibility to accept other arrangements of functional units and provides ample surfaces for control and ancillary equipment mounting.

The triangular symmetry of the integrated machine assures economy of design and development effort. As discussed above, specific packaging constraints can reasonably be accommodated without violation of the basic concept.

The command and control system uses a flexible microprocessor approach with capability for expansion to meet development needs.

4.3.4 RECOMMENDATION — Within the limits of the scope of this first funded study of continuous forming of GTP structural sections and their subsequent assembly into a continuous beam, the predesign presented for ground operation represents a reasonable data base for next phase work leading eventually to hardware development. It is therefore recommended for in-house NASA study and evaluation preparatory to next phase implementation.

CONCLUSIONS AND RECOMMENDATIONS

The following preliminary conclusions have been derived from the study work reported on herein and backed up by related IR and D analysis and test:

MATERIALS:

- o Graphite thermoplastic composite heat formable laminates can be designed to provide a wide range of desirable properties in strength and coefficient of thermal expansion.
- o Load carrying material thicknesses in the 0.6mm (0.024 in.) range and less, with a beam depth of one meter, give high-margin beam properties for preliminary experiment applications.

PROCESSES:

- o The processes involved in rolltrusion are well adaptable to flightweight implementation.
- o The rolltrusion beam fabrication machine concept developed in this study shows a specific power consumption of 0.03 kilowatt hours per meter of beam length produced.

FLIGHT EXPERIMENT:

- o The Large Space Structures Fabrication Experiment makes an excellent compatible and affordable Shuttle payload.
- o The proposed experiment will provide major data to support system applications design confidence.

FABRICATION MACHINE:

- o No high risk development is required.
- o A ground operation machine can be readily upgraded to flight status.

It is therefore concluded that the proposed experiment makes a first-class building block towards Large Space Structures program development.

It is recommended that NASA consider formalizing the Large Space Structures Fabrication Experiment as a Shuttle experiment payload for first flight in 1982.

In addition there are supporting technology areas where timely R&D efforts would advance the state-of-the-art. These critical technology areas are:

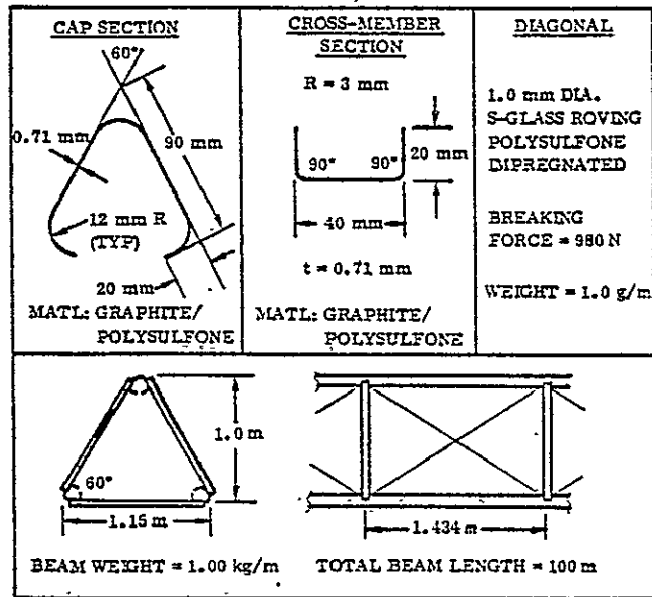
1. Investigation and Evaluation of Alternative Graphite Fibers Materials in a Polysulfone Matrix.
2. Investigation and Evaluation of Alternative Thermoplastic Resins Reinforced with Pitch Fibers.
3. GTP Laminate Characteristics Required for Rolltruding Structural Sections.
4. Design Properties of Selected GTP Laminates.
5. Effects of the Rolltrusion Process on the Properties of GTP Structural Sections.
6. GTP Strip Laminate Consolidation Techniques.
7. Processes for Continuous GTP Strip Stock Manufacture.
8. Development of 28V DC Small Cross Section Radiant Heater Elements.
9. Sensors for GTP Strip Temperature Control.
10. Fundamental Ultrasonic Weld Data for Graphite Thermoplastics.

All the above are straightforward R&D requirements. No technology break-throughs are necessary to assure beam fabrication feasibility.

APPENDIX A

BEAM SECTION PROPERTIES

BEAM CROSS SECTION



SECTION PROPERTIES

Item	Value	
I	$7.44 \times 10^{-5} \text{ m}^4$	(178.3 in ⁴)
EI	9.563 MN-m ²	(3327 MSI)
AE	43.1 MN	(9.67 Mlb)
KG	9.03 KN-m ²	(3.14 MSI)
A	334 mm ²	(0.518 in ²)

TORSION - ALLOWABLE TWIST PER BAY

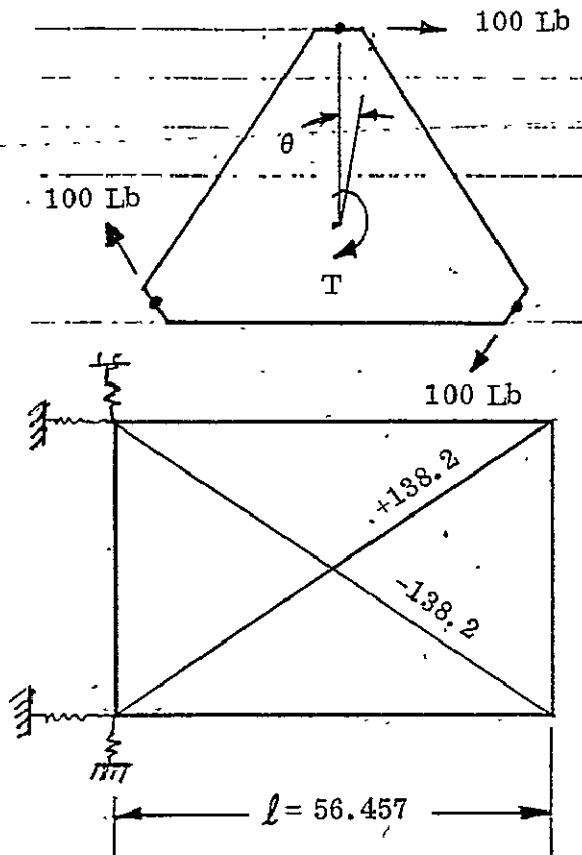
Determine the allowable twist per bay of the beam. The limiting factor is that the diagonal cords shall not go slack. With a preload of 20 lb., the twist must be limited so as not to produce cord loads greater than 20 lb. A torque applied to the beam cross section is almost entirely reacted by the cords.

A one bay model of the beam was used for this analysis and for determining the twisting stiffness.

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The beam was subjected to an arbitrary loading as shown. The results are linear.



$$T = 7854.2 \text{ in-lb}$$

The resulting rotation is

$$\theta = 0.1409 \text{ RAD } (8.07^\circ)$$

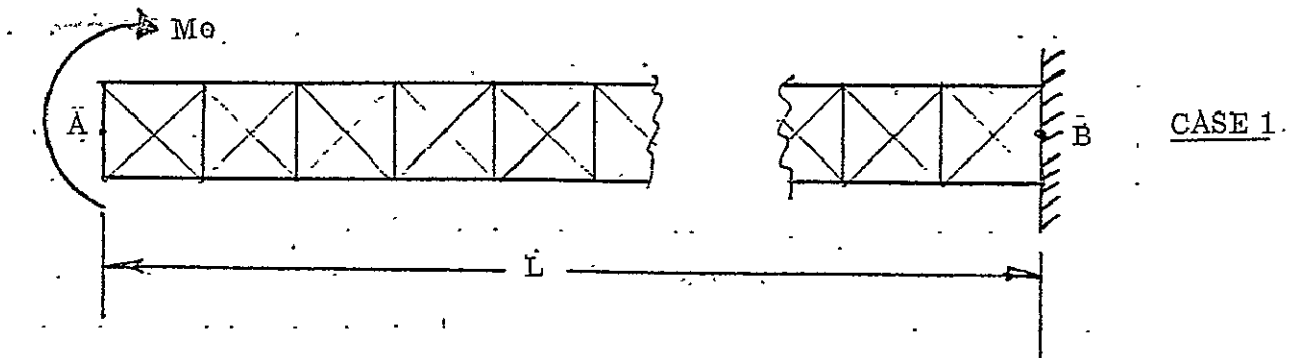
$$\begin{aligned} KG &= \frac{Tl}{\theta} \\ &= \frac{(7854.2)(56.457)}{.1409} \\ &= 3.15 \times 10^6 \text{ lb-in}^2 \end{aligned}$$

To limit the cord load to 20 lb., the twist must be restricted to:-

$$\begin{aligned} \theta &= \frac{20}{138.2} \quad (.1409) \\ &= .0204 \text{ Rad} \quad (1.17^\circ) \text{ per bay} \end{aligned}$$

MOMENT - ALLOWABLE ROTATION PER BAY

Two of the possible loading conditions that result in moments applied to the beam cross section are shown below:

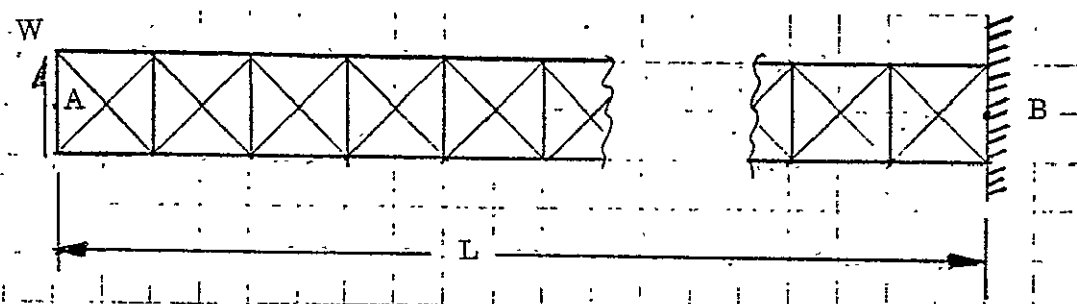


$$M \text{ max} = M_o \text{ (A to B)}$$

$$Y \text{ max} = \frac{1}{2} \frac{M_o L^2}{EI} \text{ at A}$$

$$\theta = - \frac{M_o L}{EI} \text{ at A}$$

$$V = 0.0$$



CASE 2

$$M_{\max} = WL \text{ At B}$$

$$Y_{\max} = \frac{1}{3} \frac{WL^3}{EI} \text{ At A}$$

$$\theta = \frac{1}{2} \frac{WL^2}{EI} \text{ At A}$$

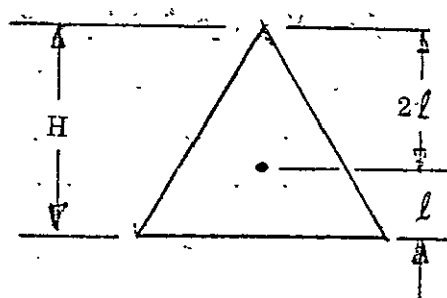
$$V = W \text{ (constant)}$$

Thus for Case 1, the allowable moment per bay is independent of length, whereas for Case 2 the critical bay is at the base and the maximum moment is a function of W and L, $M = WL$, and there may be a restriction on W that the cord loads do not exceed 20 lb.

MOMENT - MAXIMUM

For equal area caps the load in the caps due to a moment applied to the beam section is:

$$P_{\text{cap}} = \frac{M}{3\ell}$$



$$\ell = \frac{H}{3} = 13.12''$$

To determine the maximum moment, the allowable cap compressive load must be known. A stability analysis was performed for a cap which differs from this cap in the material thickness by using 3 plies of graphite rather than two. For the latter cap, the allowable was determined to be between 1480 lb. and 3068 lb. By using available data on the 2-ply crosssection and some auxiliary crippling analysis, the range of allowable load for this cap should be:

$$681 < P_{cr} > 2394 \text{ lb.}$$

Using the lower bound:

$$\begin{aligned} M_{allow} &= 3I P_{ce} \\ &= 3(13.12) (681) \\ &= 26800 \text{ IN-LB. in.lb.} \end{aligned}$$

MOMENT - MAXIMUM

The maximum shear load that can be applied without the cords going slack is:

$$V_{max} = 45 \text{ Lb}$$

This shear load then can be applied at maximum distance L

$$\begin{aligned} L_{max} &= \frac{M_{max}}{V} \\ &= \frac{26800}{45} \\ &= 595 \text{ in. (49.6 ft)} \end{aligned}$$

So for a beam 49.6 ft. or less, the shear force 45 lb. is the limiting load and for beams longer than 49.6 ft., the maximum moment of 26800 in-lb is the limiting load such that $WL < 26800 \text{ in-lb.}$

Assuming a pure moment is applied to the beam, the maximum rotation per bay is:

$$\begin{aligned} \theta_{max} &= \frac{M_{allow} L}{EI} \\ &= \frac{(26800) (56.457)}{3.327 \times 10^9} \\ &= 4.5478 \times 10^{-4} \text{ RAD (.026°)} \end{aligned}$$

APPENDIX B

SELECTED LAMINATE PROPERTIES

W-704 style graphite fabric (Table B-1) and 120 style glass fabric impregnated with P-1700 polysulfone resin were purchased from Fiberite Corporation. Parallel layup laminates were prepared from the W-704/60 and cured as follows: Insert layup in press preheated to 575F, hold 10 minutes under contact pressure, apply 200 psig pressure, hold an additional 20 minutes at temperature and pressure, and cool rapidly to room temperature. The laminate had an average cured ply thickness of 6.5 mils. A series of glass/graphite hybrid laminates were prepared as shown in Figures B-1, -2, and -3. A summary of the test program is given in Table B-2.

The test results for the W-704/P-1700 hybrid composites tested per the plan of Table B-2 are summarized in Table B-3. There is generally good translation in modulus from the basic fiber moduli. Tension and compression properties and the 10°-off-axis shear data are given as a function of temperature.

The longitudinal and transverse compression strength as well as the transverse tensile strength generally decrease with elevated temperature. The loss in strengths at 275F are smaller than anticipated, since 275F is about the maximum service temperature of the P-1700 polysulfone. The glass fabric may be influential in minimizing the above losses. The longitudinal tensile strength is a graphite fiber dominated property, and the increase at 275F may be a result of less residual stresses at the elevated temperature. The moduli show no temperature dependence except for the longitudinal tensile modulus which showed a marked decrease at 275F.

Table B-1. Construction of Fiberite Style Graphite Fabric.

Item	Description
Style Number	W-704
Thickness, Inches	0.0105
Weight (oz/yd ²)	6.61
Weave	Plain
Thread Count (Warp & Fill)	15 × 10
Warp Yarn	VSB-32T
Fill Yarn	Fiberglass 150-1/2 S-2
Width	To order
Tracer Yarns	None

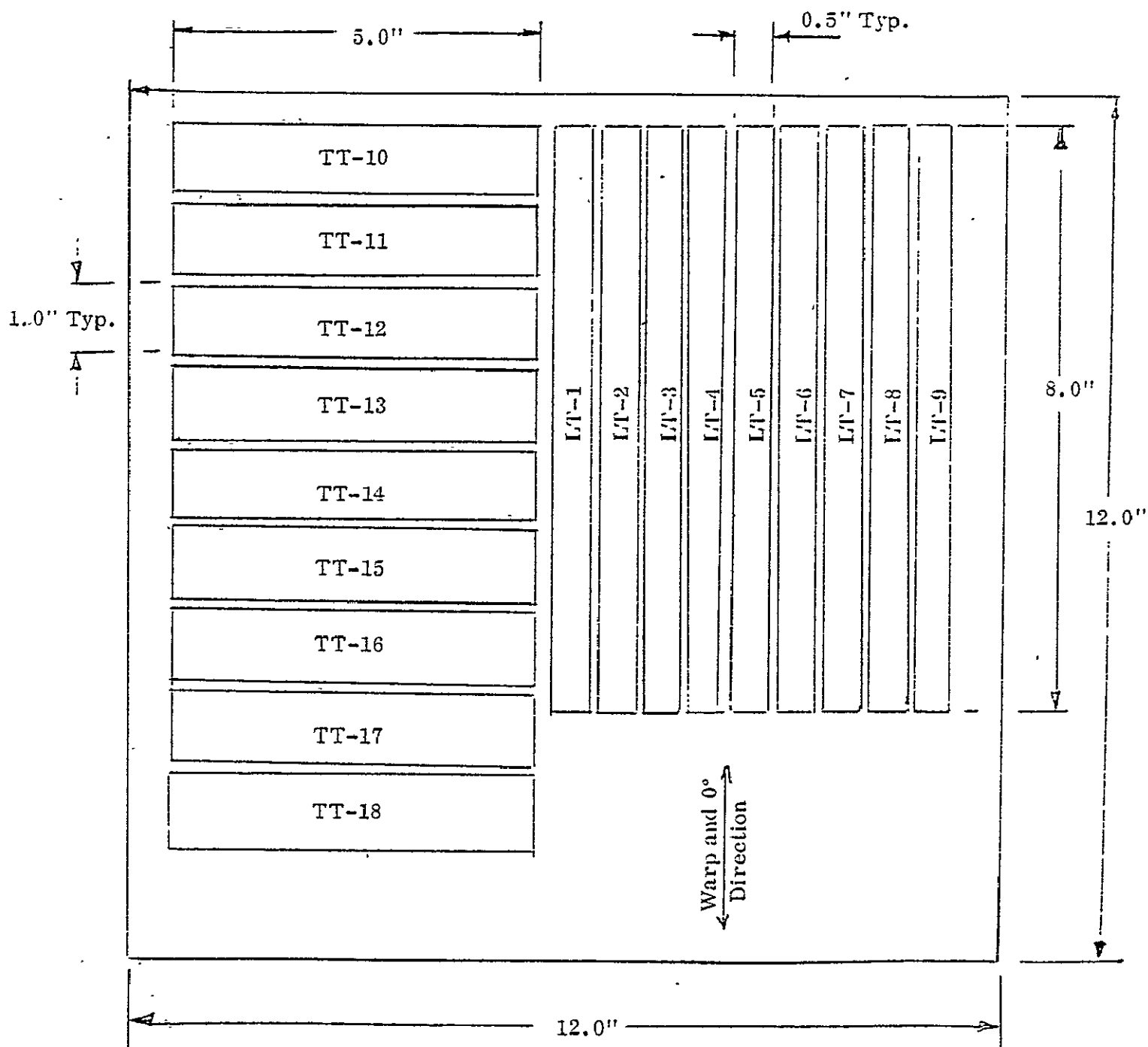


Figure B-1. Tension Specimen Cutting Plan for Hybrid Composite Panel
 Layup (120 Glass/O₂/120 Glass)_T $t_{\text{nominal}} = 0.021$ in.

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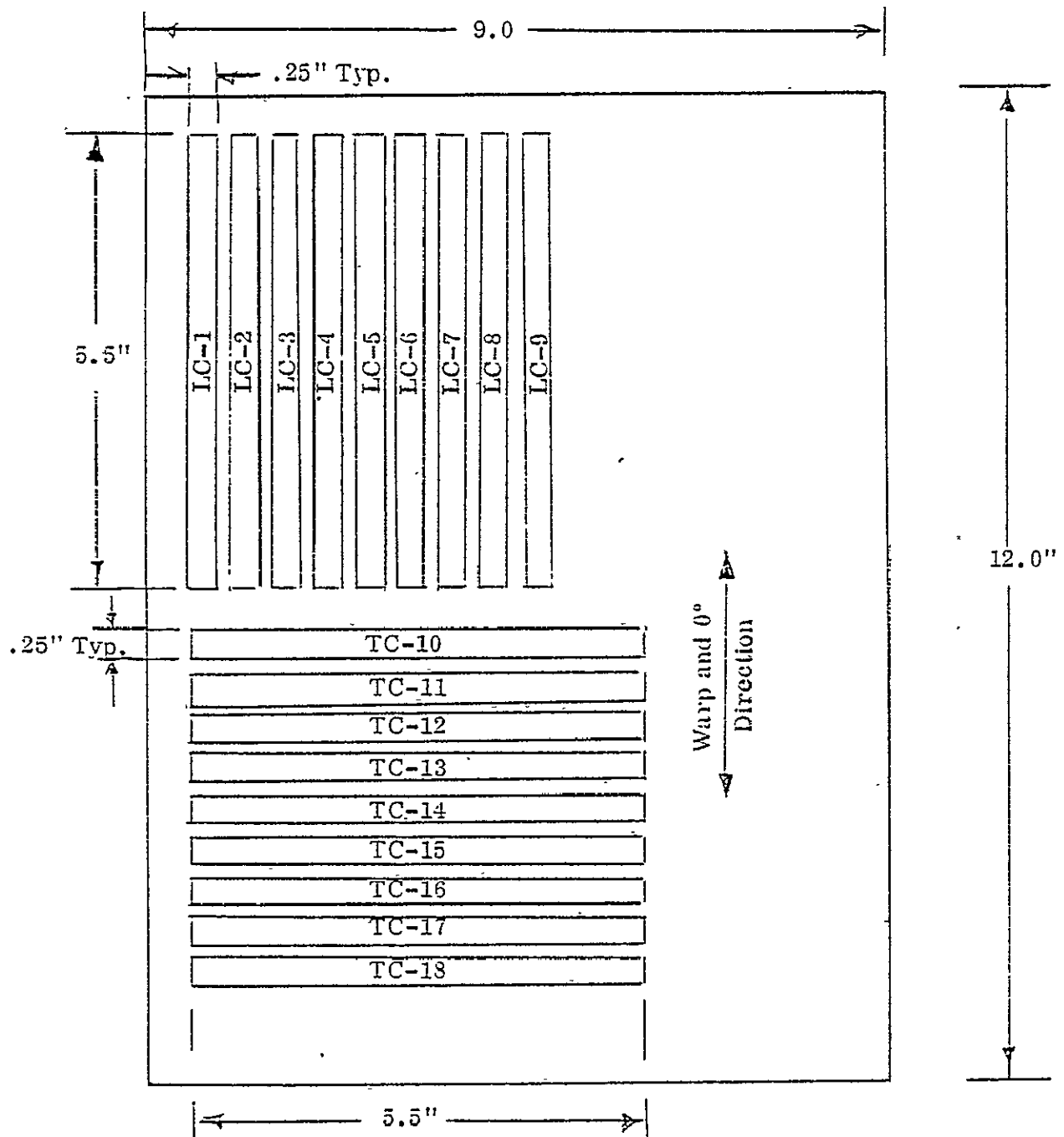


Figure B-2. Compression Specimen Cutting Plan for Hybrid Composite Panel
Layup (120 Glass/O₂/120 Glass)₆ $t_{\text{nominal}} = 0.12$ in.

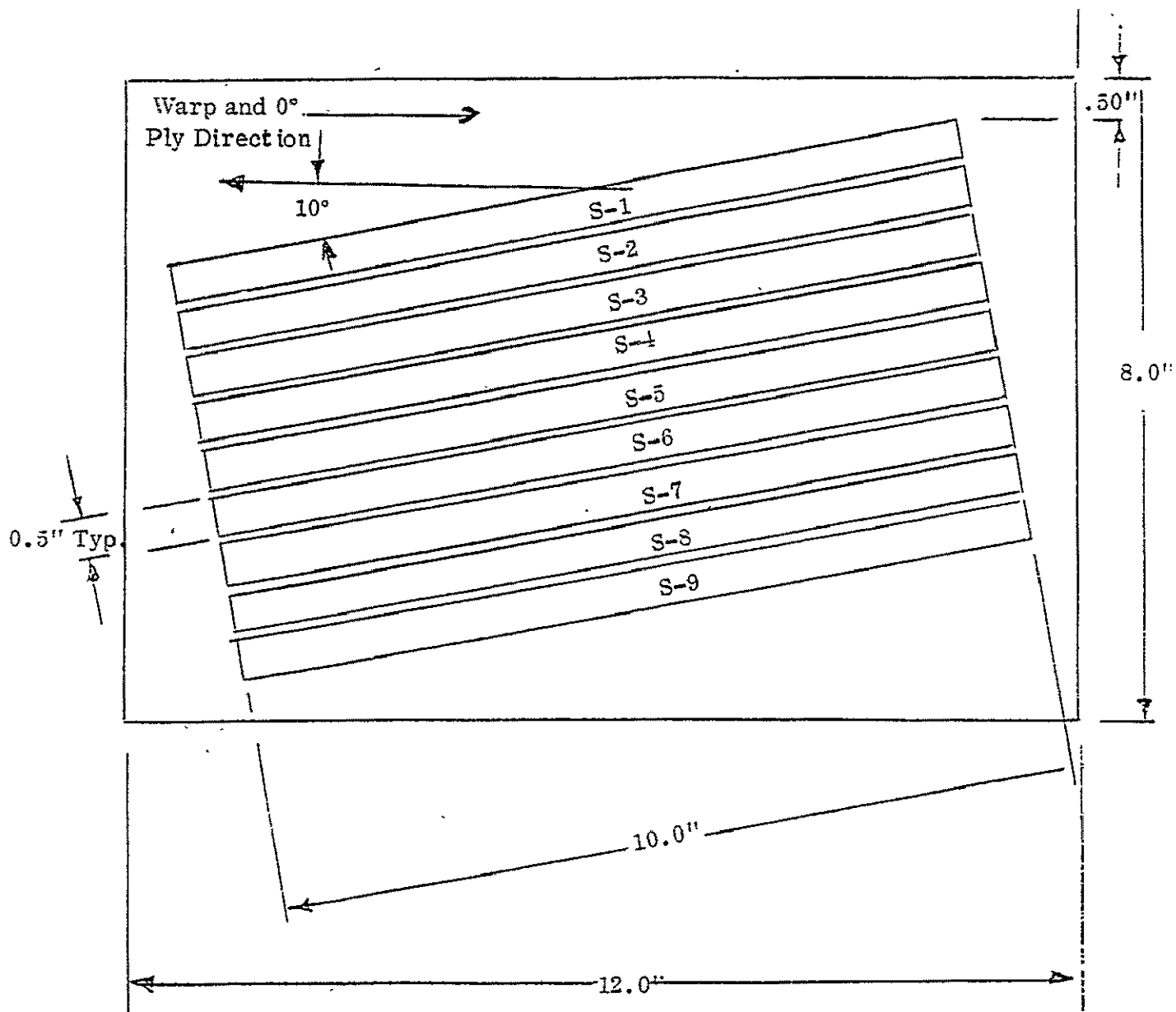


Figure B-3. In-Plane Shear Specimen Cutting Plan for Hybrid Composite Panel
 Layup (120 Glass/O₂/120 Glass)_T $t_{\text{nominal}} = 0.021$ in.

Table B-2. Summary of Test Program on W-704/120/P-1700 Hybrid Composites.

<u>Test Temp., F</u>	<u>Compression Specimens</u>	<u>Tensile Specimens</u>	<u>In-Plane Shear Specimens</u>
-67	LC-1	LT-1	S-1
-67	LC-2	LT-2	S-2
-67	LC-3	LT-3	S-3
RT	LC-4	LT-4	S-4
RT	LC-5	LT-5	S-5
RT	LC-6	LT-6	S-6
275	LC-7	LT-7	S-7
275	LC-8	LT-8	S-8
275	LC-9	LT-9	S-9
-67	TC-10	TT-10	
-67	TC-11	TT-11	
-67	TC-12	TT-12	
RT	TC-13	TT-13	
RT	TC-14	TT-14	
RT	TC-15	TT-15	
275	TC-16	TT-16	
275	TC-17	TT-17	
275	TC-18	TT-18	

Code: LC Longitudinal Compression

LT Longitudinal Tension

TC Transverse Compression

TT Transversion Tension

S In-Plane Shear

Table B-3. Summary of Test Data on W-704/120/P-1700 Hybrid Composites.

Test Temperature	Longitudinal Tension		Transverse Tension		Longitudinal Compression		Transverse Compression		10° Off Axis Shear	
	Strength, ksi	Modulus, msi	Strength, ksi	Modulus, msi	Strength, ksi	Modulus, msi	Strength, ksi	Modulus, msi	Strength, ksi	Modulus, msi
-67F	41.6	16.6	30.0	1.80	24.3	19.5	16.2	1.97	4.8	2.48
	41.8	17.0	30.0	1.67	31.3	18.0	15.9	2.00	4.6	2.39
	45.5	16.4	29.3	1.56	31.5	19.4	14.0	2.10	4.5	1.91
$\bar{X}$	42.9	16.7	29.7	1.71	29.0	19.0	15.4	2.04	4.6	2.26
Std. Dev.	2.2	0.31	0.58	0.17	4.1	0.84	1.19	0.10	0.15	0.31
RT	37.7	19.8	23.8	1.09	30.8	16.8	13.4	1.99	3.9	1.39
	36.3	18.7	23.3	1.84	33.1	16.2	14.1	1.98	3.8	1.17
	35.8	18.5	25.0	1.88	28.3	16.9	13.8	1.98	4.1	1.25
$\bar{X}$	36.6	19.0	24.0	1.80	30.7	16.6	13.8	1.98	3.9	1.27
Std. Dev.	0.98	0.70	0.87	0.10	2.35	0.38	0.35	0.01	0.15	0.11
276F	43.2	14.4	19.3	1.58	24.6	16.6	8.2	1.81	3.3	1.40
	41.2	15.6	24.1	1.57	27.7	15.4	8.9	1.74	3.3	1.58
	45.6	14.0	23.1	1.53	27.7	20.0	8.0	1.50	3.3	1.35
$\bar{X}$	43.3	14.7	22.2	1.56	26.7	17.3	8.4	1.68	3.3	1.44
Std. Dev.	2.2	0.83	2.53	0.03	1.79	2.39	0.47	0.16	0	0.12

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